AIRBORNE PARTICULATE MATTER

An Introduction to Measurement Techniques and Commercial Instruments

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Ministry of the Environment

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AIR RESOURCES BRANCH

Technology Development & Appraisal Section
Special Studies & Programme Planning Unit

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AIRBORNE PARTICULATE MATTER - An Introduction to Measurement Techniques and Commercial Instruments

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I. ABSTRACT

Fine particles suspended in the atmosphere affect air quality directly. Meteorological and health effects of aerosols depend on the particle size as well as particle concentration in air. With a maximum observed particle radius of about 120 µm, the size of airborne particulate covers a range of approximately five to six orders of magnitude. To sample aerosol particles over such a wide size spectrum with a single apparatus is not feasible. In fact, particles smaller than 0.01 µm are very hard to detect with any existing technique.

Current research has shown that the typical aerosol mass concentration is bimodal with peaks near 0.5 µm and 8 to 10 µm.[(7),(55)] Separation of fine particles from coarse particles appears to be an effective means of monitoring atmospheric particulate pollutants.

Most of commercial aerosol instruments determine the particle mass concentration or particle size distribution indirectly from the measurement of the particle's physical properties. Therefore, the accuracy of these measurements depends very heavily upon the calibration of the instruments. A knowledgeable and skillful operator is almost necessary for some sophisticated aerosol sampling systems.

Different particle sampling instruments should be chosen for different sampling purposes and sampling conditions. Concise descriptions of aerosol sampling equipments, which are readily available from major commercial sources are presented with theories and suggestions.

II. RECOMMENDATIONS

The concept of relating measurable aerosol parameters to aerosol effects has stimulated a trend in developing instruments for determination of aerosol concentration and composition as a function of particle size. In view of this development, the following recommendations are proposed for the improvement of monitoring of suspended particulate matter in ambient air.

1) It is anticipated that there will be new aerosol instruments, based on different operational principles, developed and commercially available in near future. Therefore, an ongoing literature survey of aerosol devices is recommended.
2) Exhaustive evaluations of selected available aerosol instruments, particularly those able to yield particle size information in a high time resolution period, should be undertaken as soon as possible.
3) A literature survey, along with an experimental assessment of selected new filter media should be conducted.
4) A new pollution criteria based more heavily on the potential health effects of aerosols (instead of total particulate mass loading or soiling index) should be developed.
5) Paper tape samplers should be used only for monitoring known emission sources whilst the ambient air should eventually be monitored by instrumentation that yields size

information as well as mass concentrations of the particulate matter.

6) Most of "Hi-Vol" samplers used for the network monitoring should gradually be equipped with particle sizing attachments to separate collected particulate matter into at least two size fractions "respirable" and "non-respirable" (cut-off size of about 5 µm).

7) The size distribution of suspended particulate matter, and the ratio of the respirable to the total particulate loading, at major urban and industrial areas should be determined. This would allow the determination of size information on atmospheric particulate matter with existing "Hi-Vol" data.

III. INTRODUCTION

Particulate matter exists in air as one of the constituents of our atmosphere. A wide range of concentrations, varying from about 10^7 to 10^{13} particles per cubic meter of air near the ground has been reported.[1]

The background number concentration of suspended particles in very clean air has a typical value of 3×10^8 particles/m^3 (air).[2] The average mass concentration of the cleanest continental air is about 12 $\mu g/m^3$ (air).[3] In an urban area, the concentration of airborne particles is highly variable and usually ranges from a few to a several hundred micrograms per cubic meter, depending upon the local sources and the local meteorological conditions.

The range of particle size has been measured from 10^{-2} μm to 10^2 μm with very poor knowledge about the small end of the size spectrum. In fact, particles of sizes below 0.1 μm have been studied little, because of the lack of a satisfactory measuring method. It is understandable that there is no single technique or instrument which can measure aerosol particles covering the whole size range of more than five orders of magnitude. Recent research has shown that mass and volume distribution of atmopsheric particles are bimodal with peaks near 0.5 μm and 10 μm[7],[55] (see Fig. 1 and Fig. 2). This finding suggests a new concept in ambient aerosol measurements and leads to a new trend in designing practical and efficient instruments for environmental use. A diameter of 2 μm appears to divide atmospheric particulate matter into two very different groups. Evidence indicates that a much larger fraction of the fine particles (radius $\leq$ 1 μm) than the coarse particles (radius $>$ 1 μm) in air are associated with

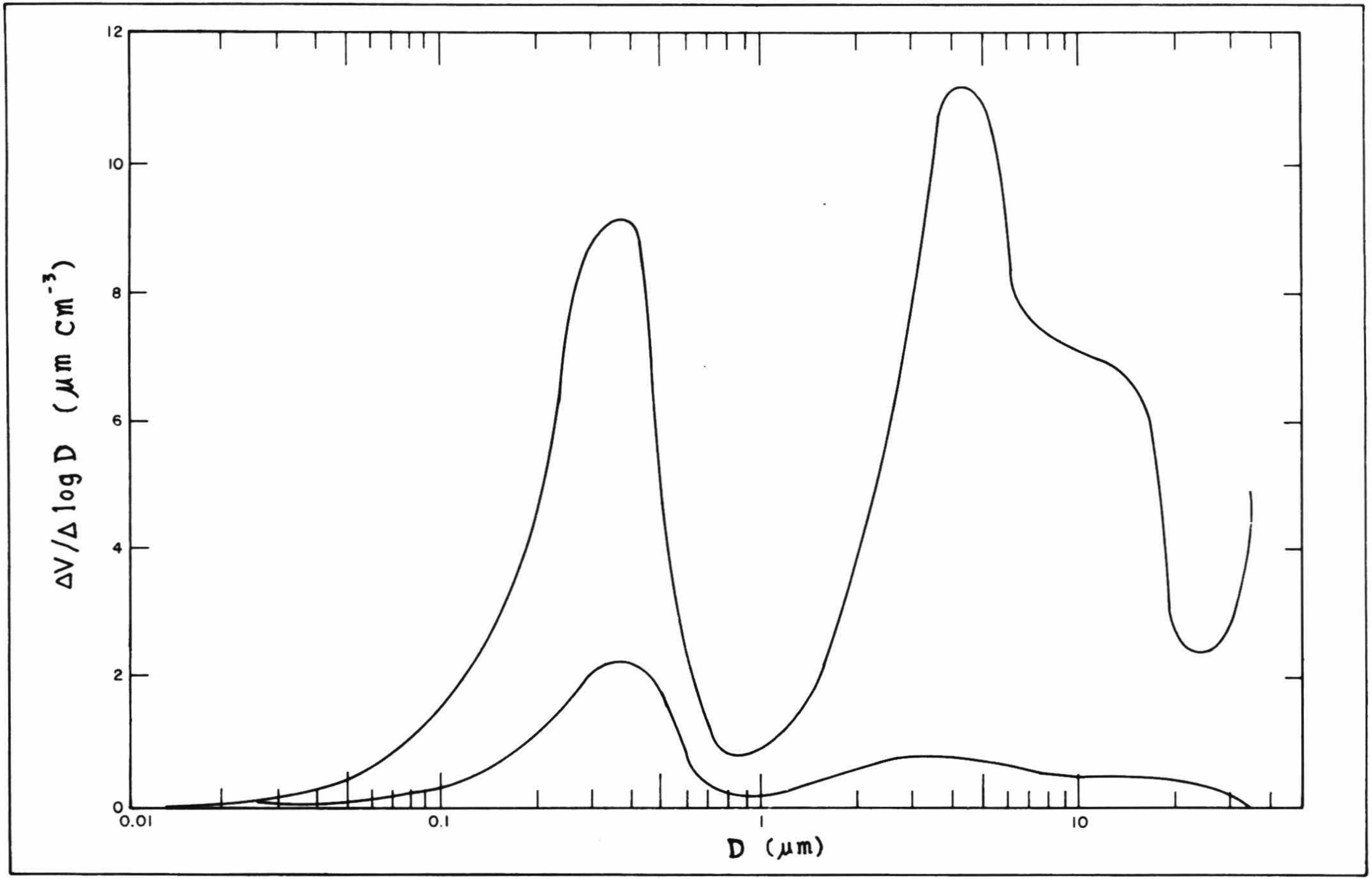


FIG. 1 A COMPARISON OF THE BACKGROUND AEROSOL VOLUME DISTRIBUTIONS DURING A VERY CLEAN PERIOD AND A PERIOD WITH HIGHER TOTAL VOLUME AT A REMOTE DESERT SITE IN SOUTHERN CALIFORNIA (AFTER SVERDRUP ETAL[49])

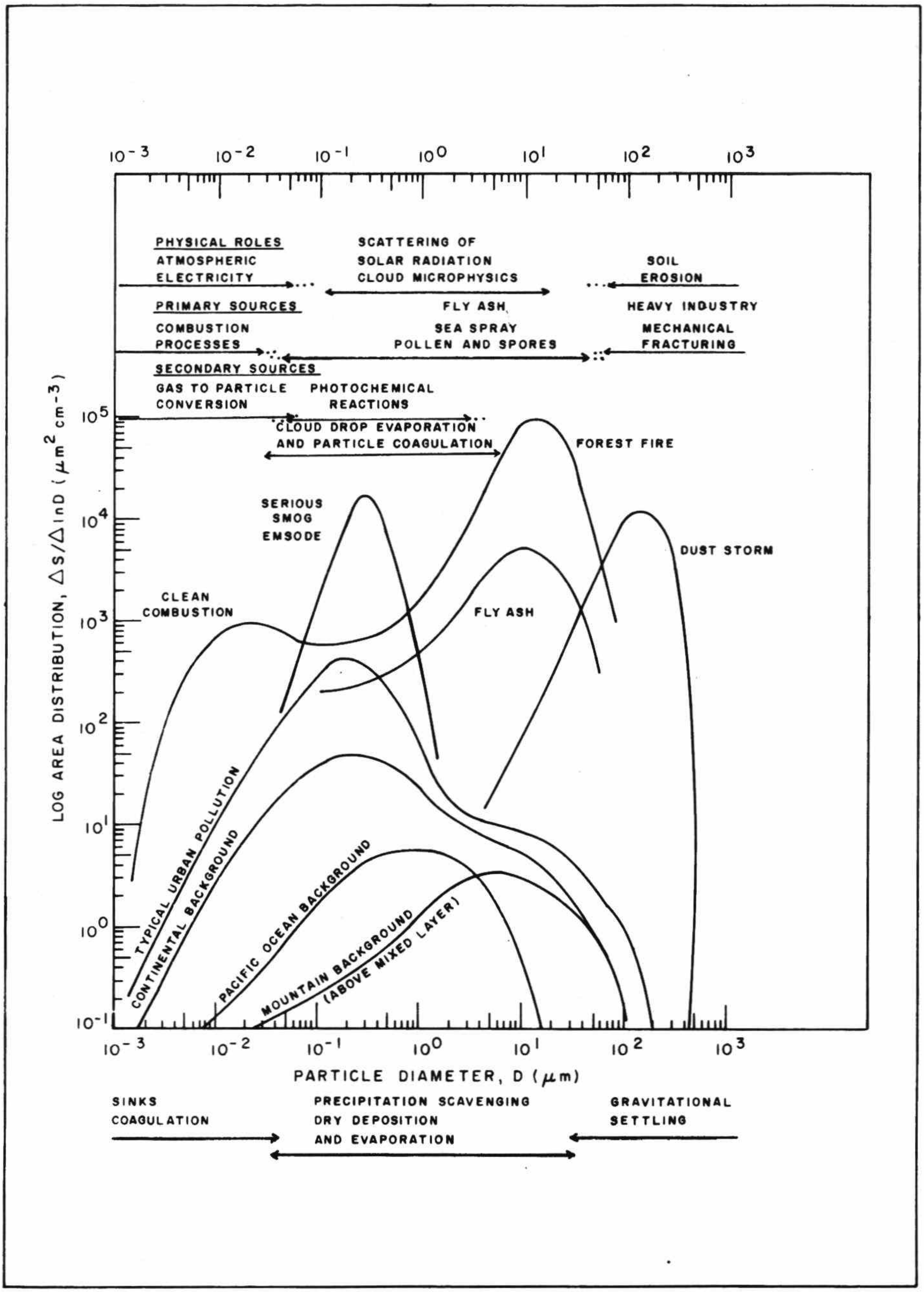


FIG. 2 A QUALITATIVE INDICATION OF SOME OF THE "STRUCTURE" OF THE PARTICLE SIZE "SPECTRA" (AFTER SLINN[50])

anthropogenic sources.[7] The coarse particles result primarily from mechanical processes such as rubbing, grinding and weathering. It is obvious, because of gravitational settling, that coarse particles have relatively short residence times in the atmosphere. Usually they are airborne for less than a few days. These large particles are often big enough to be filtered out by the upper respiratory tract before they can reach the deep lung[4] (see Fig. 3). They are thus also called "non-respirable" particles.

On the other hand, the formation of fine atmospheric particles involves complicated physical and chemical processes that convert gases into particulate matter.Unlike their large counterpart, submicron particles posses a high degree of penetration and retention in the human respiratory system. They are thus a more serious health hazard. In addition, the concentration of fine particles in air has an important influence on atmospheric visibility. They (especially in the size range from 0.1 μm to 1 μm) also cause the condensation of clouds and have very significant precipitation effects.[15] On the average, these fine particulates stay airborne for more than a week[2] and are believed to be able to reach a distance of 1,000 kilometers or more from their source.[6] Recent studies[7] show that the mass concentration of submicron particles varies by a factor of up to roughly 15 between clean and polluted air while the total particulate mass may only change by a factor of 5. Thus the concentration of particles in the submicron range is a much more sensitive measure of

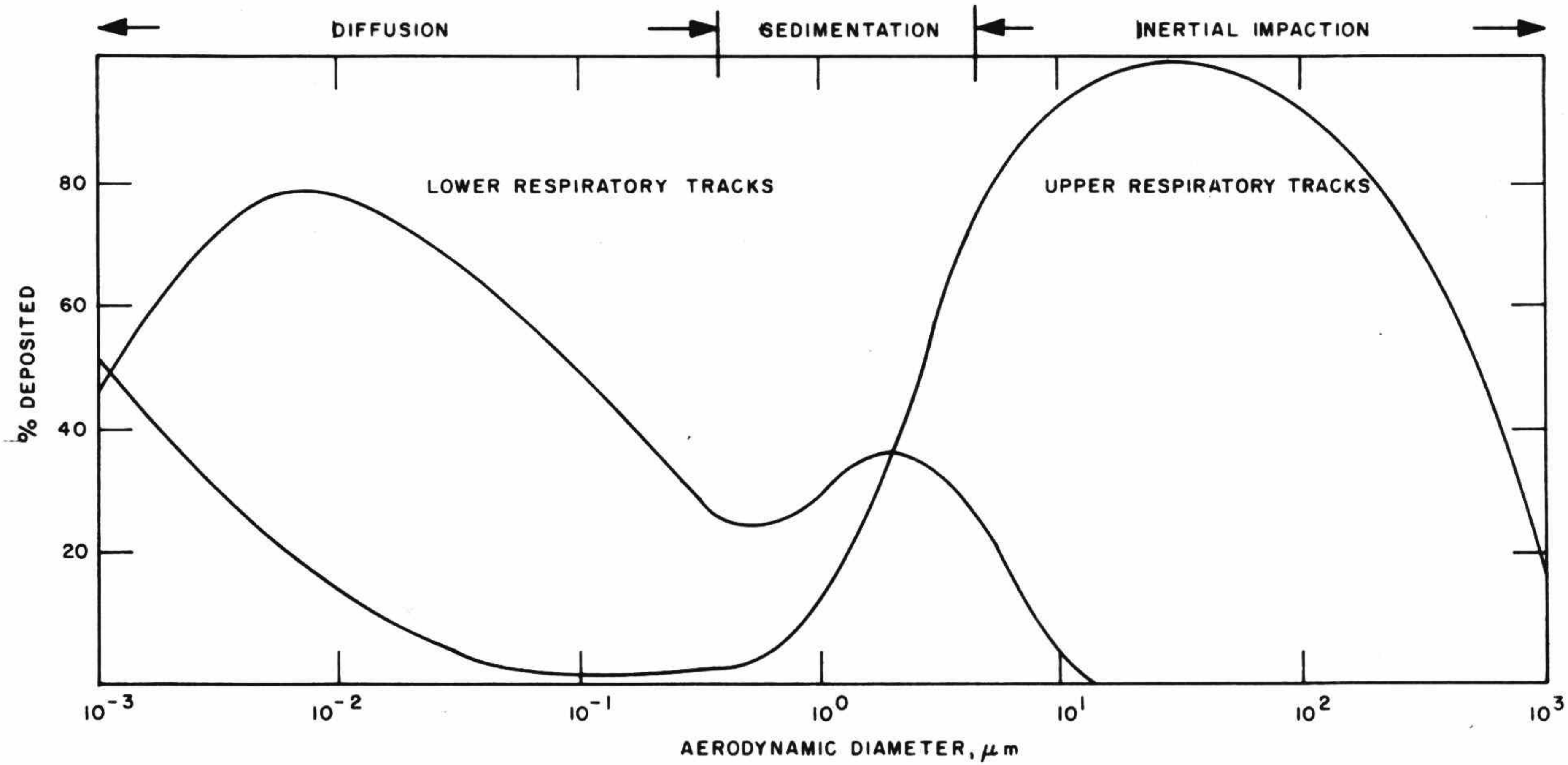


FIG. 3 SIZE – DEPOSITION RELATIONSHIP FOR PARTICLES OVER A RANGE OF DIAMETERS (ADAPTED FROM CARPENTER ETAL[51])

air pollution than the total atmospheric airborne particulate loading. Consequently, current efforts have been directed towards designing aerosol instruments to detect airborne particles in two or three size fractions, for a more realistic measure of air quality.

Although sometimes it is practical to measure only the total mass concentration of particles from a known and characterised emission source, a detailed study of particle size distribution and their chemical compositions are often valuable in pollution control. To use aerosol sampling devices effectively, an understanding of the operational principles and limitations of the instrument is essential.

IV. AEROSOL PARTICLE MEASUREMENT TECHNIQUE USED IN COMMERCIAL INSTRUMENTS

Commercial airborne particulate sampling instruments range from simple samplers collecting particles from air for the subsequent analyses, to complicated devices, giving real time readout from their built-in analyser. Even though numerous aerosol instruments are available from various commercial sources for the measurement of particle concentrations and size fractionation, there are only four main basic measuring techniques. These are: (1) filtration (2) inertial separation (3) radiation extinction (4) electrostatic and thermal precipitation.

In practice, filter samplers and inertial devices are very commonly used because of their simplicity and low cost. The particles collected by these methods can also be preserved for later analyses (shape, size and chemical composition, etc.). However, these instruments have rather uncertain efficiency for very fine particles and generally cannot be used for sampling liquid droplets or volatile particles.

The accuracy of optical devices are highly variable because they assume all particles in ambient air possess same optical characteristics exactly like the artificial aerosols used for the calibration of the instrument. Besides, they are useful only for particles in the size range between 0.1 µm and 10 µm.

The precipitators are high efficiency instruments for submicron particles in theory. However, the results of these measurements have yet to be compared extensively with other alternate techniques to establish their practical value.

To study or measure atmospheric aerosols covering the whole size spectrum, more than one instrument is needed. For the selection of aerosol measuring devices, it is useful to discuss them in groups according to their basic operational principles.

A. FILTER SAMPLING SYSTEMS

The basic elements of a filter system for collecting aerosol particles are the filter, filter holder (a mechanical support to keep the filter in place) and air mover (e.g., a pump). When the sampled air is forced to go through a filter, a large fraction of the suspended particles are retained by the filter. Usually an air flow meter and a flow regulator or a gas meter are also used to measure the volume of sampled air. The sampling time of a filter system is determined by the filter media, filter holder (type of the filter support) and the volumetric capacity of the air mover. In spite of the fact that all filter systems tend to shatter the collected particles, this sampling technique appears to be most straight forward and most versatile. Although no single filter medium can be used for all sampling purposes, there is a great variety of filter media commercially available for almost any specific application. The following is a background discussion of theory to help the selection of filter media for various sampling needs.

(a) Filtration Theory:

All filters separate particles from their carrying fluid by combined mechanisms of direct interception, inertial impaction, Brownian diffusion and electrical attraction. The direct interception occurs only when particle size is larger than the opening of the filter structure. It should be noted that direct interception is often not a dominant mechanism. For instance, particles slightly smaller than the void of the

filter are collected efficiently by impaction . Since particles have larger inertia than the air molecules, while air flow changes its route through the gaps in the filter, particulate matter tend to keep their original direction and strike the filter body.

Brownian diffusion plays an important role in capturing small particles, especially when the concentration of extra fine particles is high. The efficiency of this mechanism increases with decreasing air velocity. The diffusional separation of particles takes place on both the outside surface of the filter and on the surface of the filter void.

A certain fraction of atmospheric particulate matter carries random electric charge. Filters are also charged electrically to a variable extent from the friction of passing air flow. Therefore, a filter acts like a diffusion battery to attract charged particles when it is in use.

Different filter media have operative different combinations of the above-mentioned mechanisms and thus have different particle retention efficiencies.

(b) Filter Media

The collection efficiency and usefulness of a filter sampling system are mainly dependent on the filter media utilized. Various filter media have various chemical backgrounds. If particles of a certain element or compound are to be analysed, filter media which have high or variable blanks of that element or compound should be avoided. Some filtering materials

are sensitive to certain chemical vapours and may tend to convert certain gaseous pollutant into particulate matter. Therefore, one also has to consider all co-existing contaminants in air while selecting filter media. The following prêcis and Table 1 is intended only to provide a very brief summary of available media according to their composition.

(1) Glass Fiber Filters:

Commercial Examples:

Gelman Type A, MSA 1106BH, Whatman 40, Whatman 81

Flow Rate:

About 0.004 m^3 (air)/min-cm^2 or 0.8 ft^3/min-in^2

Efficiency:

Very high[(8),(9)] (see remark (i) and Table 2)

Advantages:

(i) chemically inert for most gases[(8)]

(ii) high efficiency for all particles[(8),(9)]

(iii) little pressure drop[(9)], no severe clogging problems.[(54)]

(iv) small hygroscopicity[(9),(54)]

(v) resistant to high temperatures[(9),(54)]

(vi) good extractability for chemical analyses[(10)]

Disadvantages:

(i) relatively expensive

(ii) large blank for sulfate[(8)] (see remark (ii)) and Si, Na, Al, Ca, B, Mg, Zn, and K, etc.

(iii) high alkanility - can convert some gases (e.g., SO_2, H_2SO_4, HCl), into particulate matter.[8],[10]

(iv) not easily examined optically

(v) diverse filter quality and poor uniformity in construction[9]

(vi) weight loss (loss of fibres) when in use[9]

Remarks:

(i) less efficient varieties are available for special applications[54]

(ii) sulfate blanks can be reduced by prewashing the filters with hot distilled water[10], however some properties of the filter may be changed by washing

(iii) glass fibre filter with "Hi-Vol" sample is the most widely used non-size selective particle sampling method in the U.S. and Canada.

(2) Cellulose Fiber Filters:

Commercial Examples:

IPC 1478, MSA Type S, Whatman 1, Whatman 41, Whatman 50, Whatman 541

Flow Rate:

Highly variable[9]

Efficiency:

From very low to very high depending on the filter and the size of particles[12] (see Table 2).

Advantages:

(i) low pressure drop[9]

(ii) good mechanical properties (e.g., thin but strong) for handling[9]

(iii) inexpensive and easily obtainable

(iv) no obvious conversion of SO_2 into sulfate particles[8],[13]

Disadvantages:

(i) generally lower efficiency for sub-micron particles compared to other filter media.[8],[14]

(ii) hygroscopicity: weighing difficulty[54]

(iii) non-uniformity: variable efficiency

(iv) background sulfate-about 47 X 10^{-9}g $(SO_4^{=})/cm^2$

(3) Polystyrene Fiber Filters:

Commercial Examples:

Delbag Microsorban (see remarks below)

Flow Rate:

Comparable to glass fiber filter[9],[11]

Efficiency:

Relatively high[11],[15]

Advantages:

(i) reasonable efficiency for particle of all sizes[15]

(ii) soluble in aromatic hydrocarbons for particle analyses[9]

(iii) very low blank for most metal elements

Disadvantages:

(i) some particle extracting difficulties[13]

(ii) high and variable sulfate blank (in 0.025 $\mu g/cm^2$ range)[13]

(iii) mechanically fragile

Remarks:

Delbag Microsorban are German made filters.

(4) Membrane Filters:

Commercial Examples:

Gelman GA, Millipore AA, Millipore PH, Millipore SS, Nuclepore®

Flow Rate:

Varies from 0.001 $m^3/min\text{-}cm^2$ to about 0.1 $m^3/min\text{-}cm^2$ depending on pore size.

Efficiency:

Very high for submicron particles[16] (see Table 2) may have a minimum efficiency at a certain particle size (see Fig. 4) determined by pore size and air velocity.

Advantages:

(i) collected particles are easily analysed optically or chemically

(ii) high retention for very fine particles[8],[17]

(iii) relatively uniform pore size[54]

(iv) low residual sulfate[8]

(v) mechanically strong

(vi) collection efficiency varies with different pore size and sampling flow rate (see Fig. 4)

Disadvantages:

(i) low flow rate

(ii) large pressure drop and also pore clogging problems

(iii) limited sample volume (efficiency greatly reduced after a single layer of particle is collected).

(c) Summary and Comments:

Particle sampling systems using filters as the collecting medium is a simple and very useful means in sampling atmospheric particulate matter.

Like all other aerosol equipment, there is no all purpose filter medium which can be used for collecting all particles under all sampling conditions. However, with careful selection, one can almost alway find suitable filter media available for any specific application. The filter can be used either alone for gross particulate concentration measurement or as part of a filter pack for particle size discrimination. (8), (9) Some filter have been used successfully for separating "respirable" particles from coarse dust in air .

"Hi-Vol" samplers are typical filter systems readily available from various commercial sources. They are the standard aerosol samplers for total mass concentration in North America. With cascade impaction attachments, "Hi-Vol" samplers have also been used for size selective sampling. A successful filter sampler

can also be constructed for any specific application if one chooses the filter medium and other necessary components cautiously. In short, filter sampling systems are versatile aerosol instruments useful for sampling particles in ambient air as well as various industrial emissions.

TABLE 1

Comparison of Filters for Aerosol Sampling

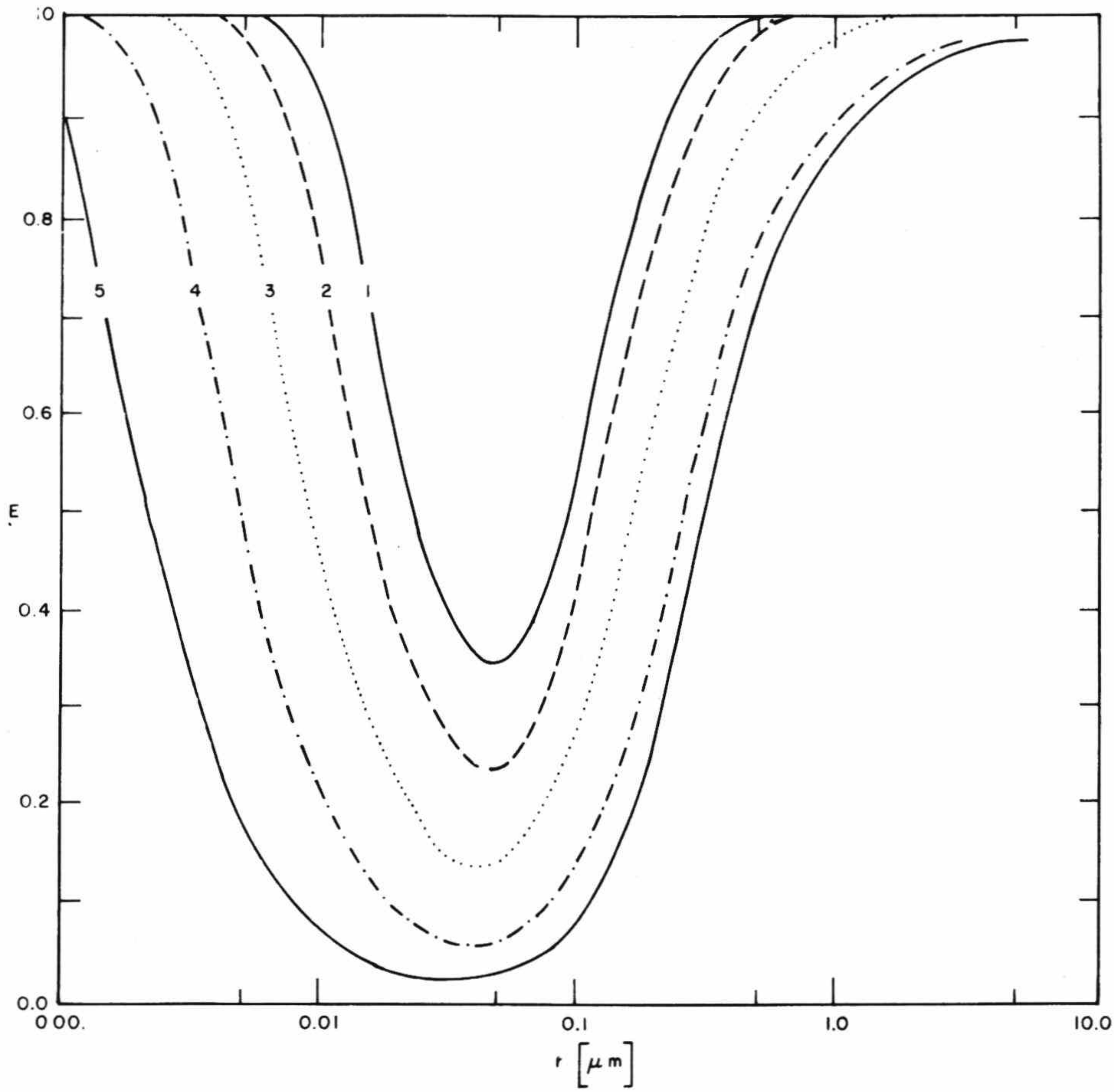
Filter	Collection Efficiency	Flow Rate	Cautions
Cellulose Fiber	Variable	Variable	Highly Hygroscopic
Glass Fiber	High	High	High metal blanks and high alkanility.
Membrane	Variable	Low	Pore clogging problems.
Polystyrene Fiber	High	High	Fragile

TABLE 2

SELECTED DATA ON FILTERS USED IN AEROSOL SAMPLING

Filter	Mean pore diameter,[a] um	Air flow Rate [a,b]	Thickness,[a] µm	Efficiency, %, at 5 cm/sec face velocity — Particle diameter 0.03 µm	0.3 µm
Fiber:					
Gelman Type A	NA[d]	-	~450	>98[a]	>99.7[a]
Gelman Type E	NA[d]	-	~450	>98[a]	>99.7[a]
Whatman 41	NA[d]	-	~300[c]	58.9[c]	22.4
Gelman membrane:					
GA-1	5.0	20	140	-	-
GA-6	0.45	6.6	140	>99[c]	>97[c]
GA-7	0.3	4.2	140	>99[c]	>97[c]
GA-8	0.2	3.9	140	>99[c]	>97[c]
Millipore membrane:					
SC	8.0	55	125-150	-	-
SS	3.0	20	125-150	99.9	91.2
OH	1.5	-	125-150	87.2	51.1
AA	0.8	11	125-150	99.9	97.3
HA	0.45	4	125-150	99.9	98.8
PH	0.30	3.7	125-150	>99[c]	>99[c]
GS	0.22	2.5	125-150	>99[c]	>99[c]
VC	0.10	0.49	125-150	>99[c]	>99[c]
VM	0.05	0.31	125-150	>99[c]	>99[c]
VS	0.025	0.22	125-150	>99[c]	>99[c]
Nuclepore	8.0	~100	10	5.7	10.1
Nuclepore	5.0	~100	10	18.4	14.4
Nuclepore	2.0	~50	10	43.3	28.3
Nuclepore	1.0	30	10	86.8	52.2
Nuclepore	0.8	22	10	94.6	61.9
Nuclepore	0.5	~10	10	98.7	99.3
Nuclepore	0.4	~10	10	>99c	>99[c]
Nuclepore	0.2	~4	10	>99[c]	>99[c]
Nuclepore	0.1	0.8	10	>99[c]	>99[c]

a - Data supplied by manufacturers.
b - Flow rate in liter/min-cm^2 (ΔP = 0.93 atm at 1 atm).
c - Estimated
d NA: Not applicable



1. R_o = 0.4 μm
2. R_o = 0.5 μm
3. R_o = 1.0 μm
4. R_o = 2.5 μm
5. R_o = 4.0 μm

q = 75 Cm/sec

s = 21 g/cc

where:

R_o = Pore radius of clean filter

q = face velocity of gas at filter

s = particle density

r = particle radius

FIG. 4 COMPUTED DEPENDENCY OF EFFICIENCY ON PARTICLE SIZE AND PORE SIZE OF NUCLEPORE FILTERS (After Spurny et al[52])

B. INERTIAL PARTICLE COLLECTORS

Particles in an air stream can be separated from air molecules if the air stream changes its direction suddenly. Instruments including impactors, impingers, centrifuges, and virtual impactors are designed on this separation principle using solid surface, liquid media and air volume, etc. as particle collectors. Since the separating force of this mechanism is dependent upon the particle inertia, the product of particle mass by particle velocity, $(I=M \cdot V)$ in theory, these instruments are capable of sizing particles if all the particles have the same mass density. Like the filter sampling system, subsequent physical and chemical analyses of particles sampled by inertial devices can be made for each particle size fraction.

(a) Instrumental Principles and Operational Suggestions:

The efficiency of instruments using inertia to separate and collect particles from an air stream is a function primarily of particle mass, adhesion, collecting method and stream velocity.[(20),(21),(22)] The actual particle collection efficiency of commercial instruments varies from very low to very high. They are best discussed in groups according to their different particle collecting methods.

(1) Impactors

A conventional impactor accelerates aerosol into an air jet by an air mover and an orifice. Particles are then impacted against and deposited upon a solid surface which is placed in the way of the jet stream (see Fig. 5). The collecting surface sometimes has an adhesive coating to avoid

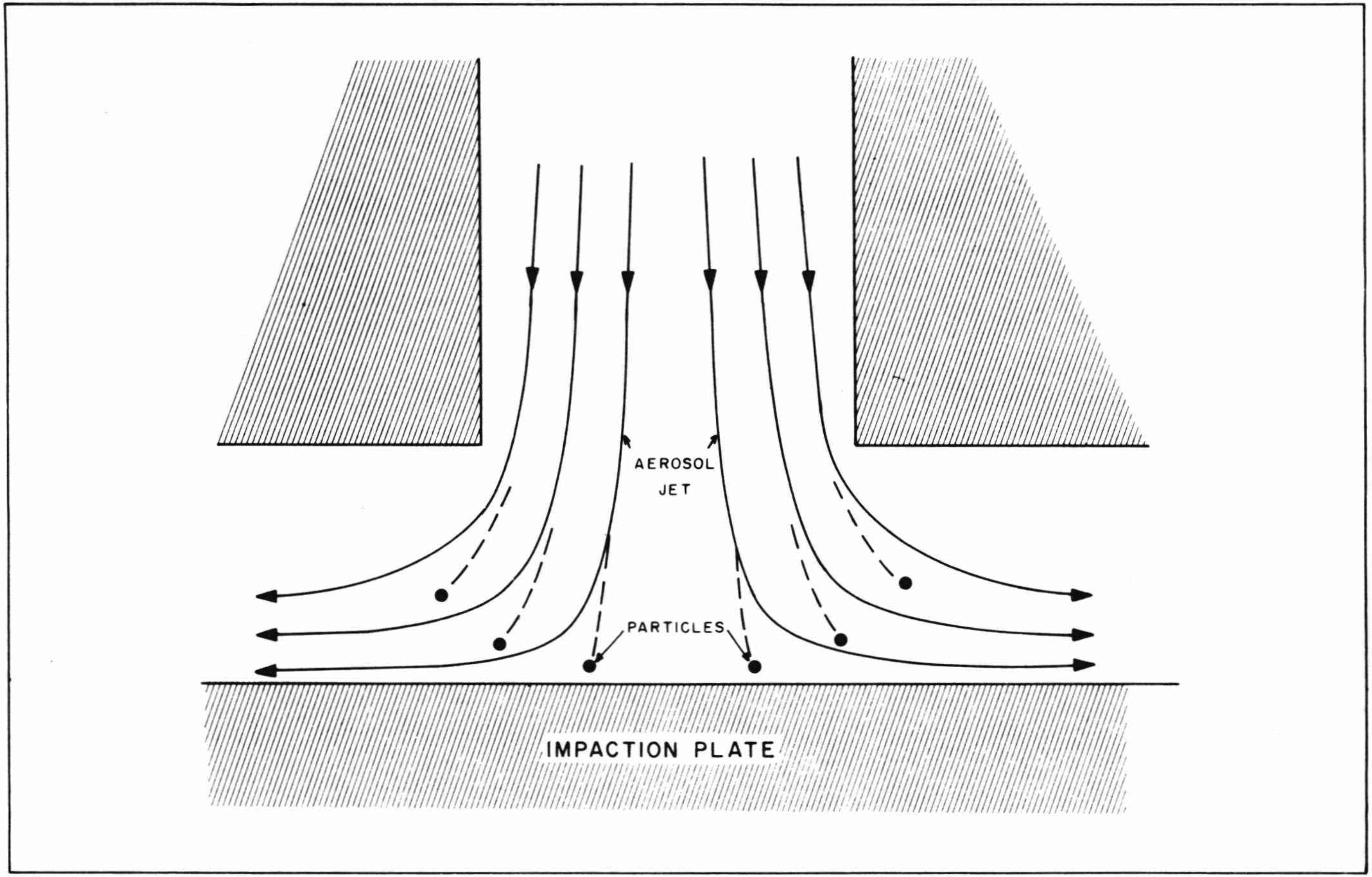


FIG. 5 SCHEMATIC OF A CONVENTIONAL IMPACTOR

blowing off of particles. The usefulness of the impactors was greatly improved by May[23] with his study on multi-stage impactors for coarse particle sizing about three decades ago. Since then, cascade impactors by various manufacturers have been used extensively in sampling polluted air and emission sources for particle size distribution. Although there have been some significant theoretical developments[23],[24] and good experimental reports about multi-stage impactors[25],[26], the actual performance of these particle sizing devices is still not fully understood.

In practical use, each impactor should be operated at its optimum flow rate which is usually suggested by the manufacturer. (Some impactors are designed for variable flow rates but the range is not very wide). An excessively high flow rate may result in particle re-entrainment. (Jet speed of 60 m/sec(200 ft/sec) or higher is to be avoided[27]. On the other hand, if aerosols are not accelerated to an adequate speed obviously some particles will escape impaction. Besides, small particles may diffuse to walls of the instrument before they reach the collecting stages. These particle losses are size dependent and thus affect the results of not only the total particle concentration but also the particle size distribution. As a consequence, high flow rate impactors (e.g., the Andersen impactor) are recommended for ambient sampling and low flow

rate impactors (e.g. Brink Canada impactor) are suggested for source testing.

It is practical to cover each stage of a cascade impactor with a light weight collection substrate. This will improve particle weighing accuracy because the collection stages of most commercial impactors often weigh more than a thousand times the particles they can collect. The commonly used substances are teflon sheets, aluminum foil, polycarbonate membrane (Nuclepore filter) and glass fiber filter material, etc. Metal substances and glass collection surface are often coated with silicone grease or agar to help retain dry particles.

Some current research has been devoted to the development of impactors measuring particles in only "respirable" and "non-respirable" fractions for practical air monitoring. Due to their small mass the submicron particles are very difficult to collect with impactors. Theory indicates that the particle collection efficiency of any impactor can be increased by reducing fluid pressure. Therefore, studies have been made to extend the use of cascade impactors in submicron range by operating the devices at very low pressure.[27]

Impactors have also been improved to give instantaneous read out recently. Piezoelectric particle micro-balances and beta gauges are now available.[28],[29] The former uses an adhesive coated quartz crystal, a well-known piezoelectric material, as the impaction surface.[30] While sampling, the crystal

oscillates in an electric oscillating circuit. Since the oscillating frequency decreases with increasing weight of the cyrstal, the total mass of particles deposited on quartz can be determined by measuring the change of the oscillating frequency.

An impactor developed by GCA company using beta ray attenuation technique for particle mass concentration has been described in detail by Doemany et al.[31] A typical instrument of this type has a constant beta source placed in the impactor nozzle. A Geiger tube receives decreasing beta radiation as particles impact on the mylar disk located above the gauge. Beta gauge theory will be discussed briefly in next section under "Nuclear Detectors".

Theoretically, these sophisticated impactors can be used for real-time particle mass monitoring. However, the actual systems are far more complicated than a conventional impactor. For instance, falsely high readings given by these instruments have been observed when relative humidity of air is high enough to condense water on aerosol particles.[32] Therefore, further study and technical refinement should be allowed for those new impactors in order to allow a fair performance evaluation.[33]

(2) Impingers

The main difference between impingers and impactors is that impingers use a liquid media, instead of a solid surface to collect particles.

The particulate matter plunges into the liquid medium from air as an aerosol jet. The jet speed of regular impingers (slightly higher than 90 m/sec or 300 ft/sec) is much faster than that of impactors. Compared to the regular impingers, midget impingers are more compact in size and are often operated at a slower jet speed of about 70 m/sec ($\sim$230 ft/sec) for more convenient operation.

Theory shows that the use of an impinger in sampling submicron particles is not practical because to retain these fine particles in the liquid it requires an ultra high jet velocity which is violent enough to fracture particles.[34],[35] Impingers are not often used for collecting airborne droplets because they cannot provide quantitative results. Other precautions in impinger sampling is to ascertain that gaseous pollutants in the air to be sampled which are soluble in the collecting liquid will not react with the impinged particles. For aerosol sizing, impingers with different jet speeds can be operated in series but the number of stage is rather limited.

(3) Centrifuges:

Due to centrifugal force, rotation of air causes airborne particles to move radially outward. The force acting on a particle which separates it from the air stream is determined by mass of the particle, velocity of the stream and the radius of curvature of the path in which air flows. The complete theory about particle separating force of centrifugal devices has been discussed by Fuch[20] and Drinker, et al.[35] Since it needs a high stream velo-

city to separate small particles from air the particle size range of a centrifuge is determined by the actual rotational speed that instrument can achieve mechanically. All centrifuges share a common set back of extremely low sampling flow rates (typically lower than 10 liter/min). Although they are valuable as precise and efficient sizing instruments (e.g. "Goetz Aerosol Spectrometer") for laboratory particle studies, they cannot be used practically for ambient aerosol sampling.

By forcing air to flow in a circular path, a cyclone is a special kind of centrifuge which elutriates aerosol particles with respect to their aero-dynamic size without rotating elements (see Fig. 6). The theory of a cyclone is more complex than that of rotation centrifuge. The theory of the cyclone has been reviewed by Lapple[(36)] in depth.

The particle collection efficiency of cyclones generally drops from very high to very low as the particle size decreases from 10 µm to 2 µm. This is a very favorable characteristic, as far as the bimodal particle size distribution is concerned. With the advantage of high sampling flow rate (higher than that of impactors), cyclone have often been used as the first stage of a sampling system in separating "respirable" particles from the total particulate loading in air. Although the particle size cut-off of cyclones is not as sharp as that of impactors, the combination of a cyclone and an impactor or a cyclone and a filter has demonstrated its practical value in field use for large volume sampling.

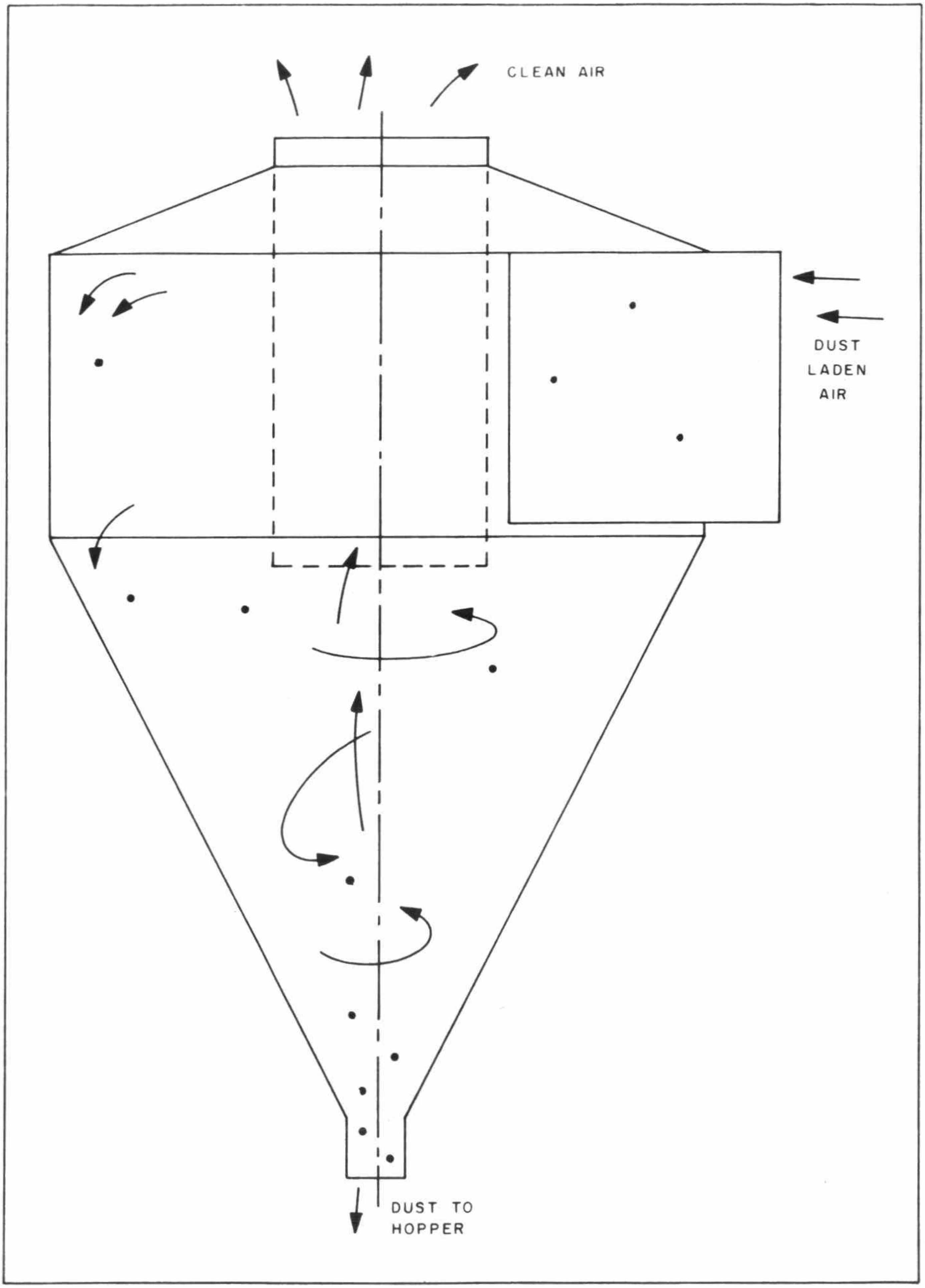


FIG. 6 LOW PRESSURE CYCLONE

(4) Virtual Impactors

Instead of a real impaction surface, a virtual impactor uses a volume of stagnating air to collect the impacting particles (see Fig. 7). Airborne particulate matter thus is separated into different air chambers according to aerodynamic size and then collected onto high efficiency filters for further physical and chemical analyses (see Fig. 8). The size separation of the impaction mechanism is not very sharp. By using the same air volume for repeated impaction processes, (conventional impactors have practical difficulties in repeating particle impaction on the same collecting surface) a virtual impactor can achieve very good size cut-off characteristics. The other advantage of the virtual impactor over the ordinary impactor is that particles can bounce from a solid impaction surface or its collected particles but not from a dead air space. Since the problem of re-entrainment of particles is eliminated, the virtual impactors can be operated at a relatively high flow rate for fast sampling. The virtual impactor can also be automated by adding the beta attenuation technique for a real-time mass measurement.[37] Commercial instruments of this type became available very recently. Extensive field evaluations are necessary to verify that virtual impactors are practical instruments for size-selective ambient particulate sampling.

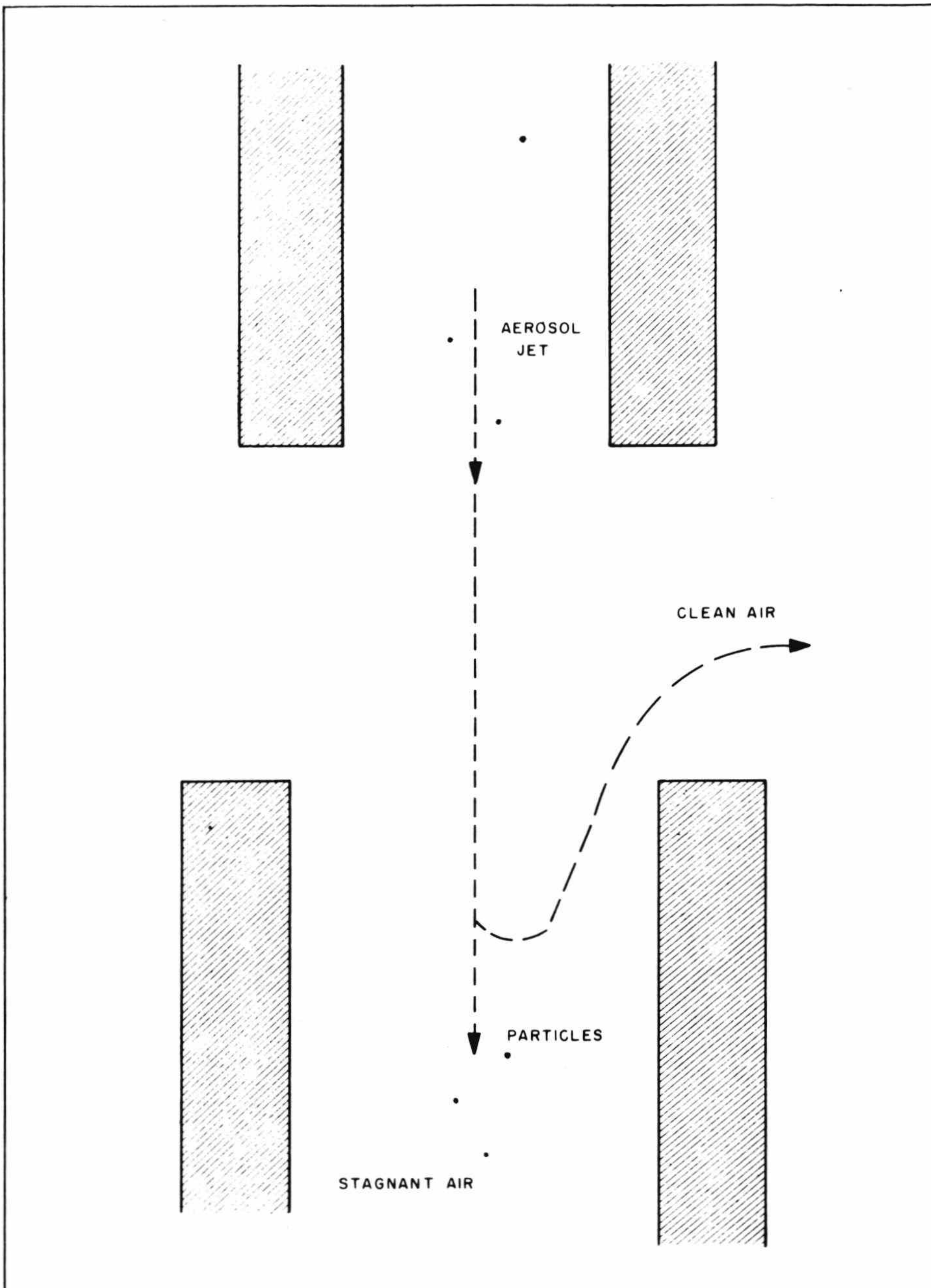


FIG. 7 SCHEMATIC OF A VIRTUAL IMPACTOR

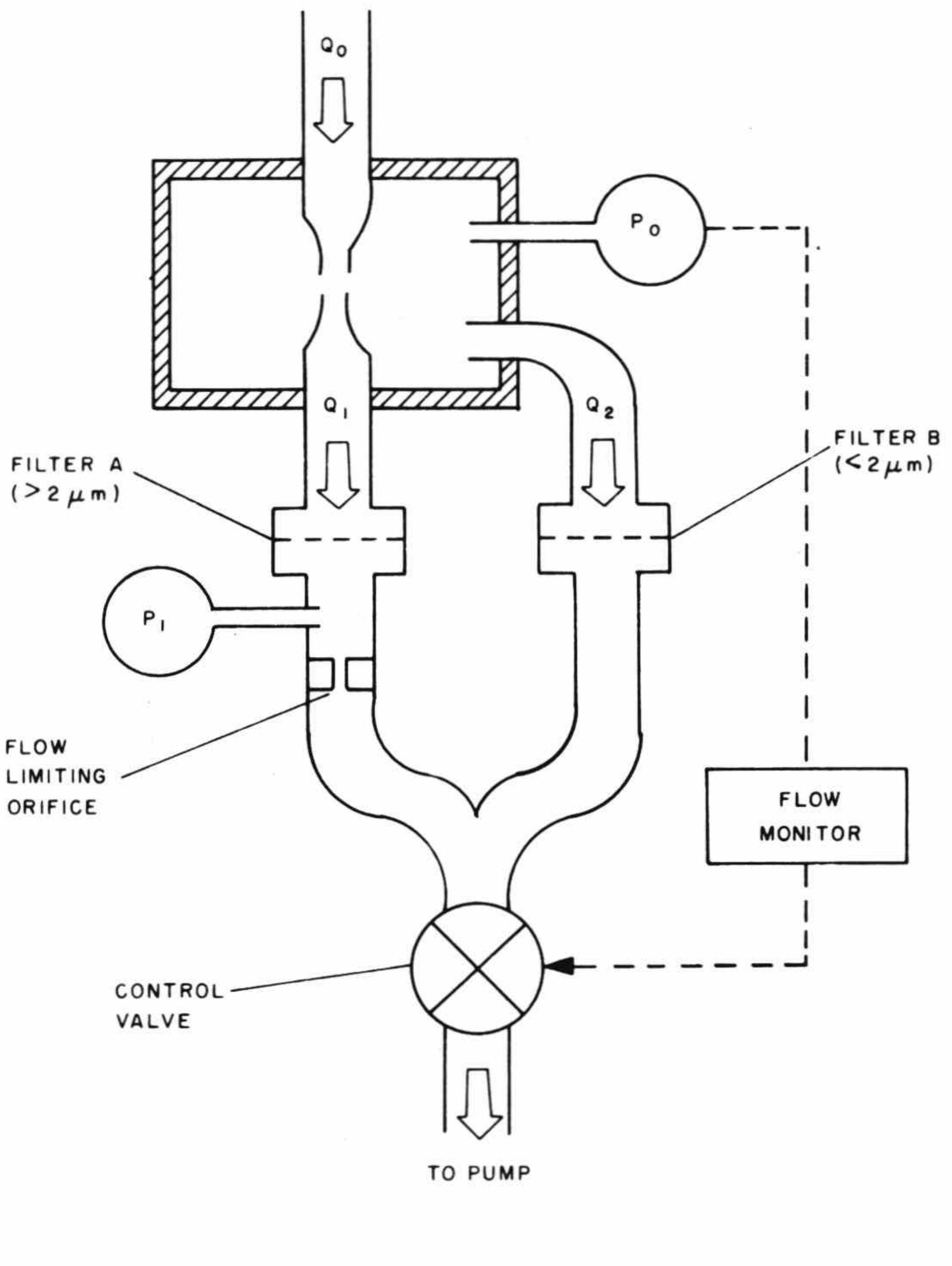


FIG. 8 SCHEMATIC OF A SINGLE - STAGE DICHOTOMOUS VIRTUAL IMPACTOR (ADAPTED FROM REFERENCE 38)

(b) Summary and Comments:

Among aerosol samplers utilizing inertial force to separate particles into size fractions, cascade impactors are the most commonly used. Although major cascade impactors on the market have been tested by various investigators, the actual performance of these devices in particle size separation are yet to be studied further. They are useful in testing emission sources for particles larger than 0.3 um. The application of the impactor for submicron particles has been limited because of the low efficiency.[27] The collected mass on each stage of a cascade impactor is often too small for analytical purposes. Error can be easily introduced into the results of measured size distributions if the multi-stage impactor is used by an inexperienced operator. Wall losses of particles between stages is one of the unsolved problems of these devices. Proper calibration is essential for all impaction instruments.

Centrifuges only have been used to collect particles in a limited particle size range around 1 um at very low sampling flow rates. Different from rotation centrifuges, cyclones have very high flow rates and have been proven by some laboratory tests that they are good substitutes for impactors if a large sample size is desired. However, the resolution of cyclones has not been satisfactory for precise work. Even though more field tests on using cyclones for particle size analysis are necessary, evidence seems to indicate that combining a cyclone with impactors or filters can make simple but efficient

systems for monitoring atmospheric aerosols in two fractions with markedly different health effects.

An impinger as a particle sampler or a particle analyser has serious theoretical limitations. The requirement of a jet speed near sonic velocity to retain submicron particles suggests that fine particles cannot be efficiently collected by this technique without damaging coarse particles.

Research efforts have been directed to develop highly efficient multi-stage virtual impactors. In spite of the complexity, an automated dichotomous virtual impactor has demonstrated its potential for sampling aerosols in both "respirable" and "non-respirable" sizes.[(38),(39)] It seems that in the near future, more inertial aerosol devices capable of giving direct reading will be available for continuous monitoring of particulate matter in ambient air.

C. RADIATION AEROSOL DETECTORS

Extinction of radiation by suspended particles includes two electromagnetic processes, namely scattering and adsorption. If the characteristics of both the radiation and aerosol particles such as the wavelength, shape, size distribution and the complex refractive index ($n = n_1 - in_2$, where n_1 is the ratio of the velocities of radiation in a vacuum and the particle, n_2 characterizes the radiation absorption of the particle medium.) are understood, theoretically it is feasible to estimate the concentration of total irradiated particles from accurate measurements of the transmitted and scattered intensities. The radiation source can be either radioactive (e.g., β ray) or optical (including ultra-violet, visible and infra-red radiation) in nature. The extinction of beta ray, described briefly in Section B, is a typical application of radioactive technique in particle detection. In this section most of the discussion will be focused on optical instruments because they are useful apparatus for measuring aerosol particles in an important size range.

(a) Instrumental Principles and Operational Suggestions:

When irradiated, aerosol particles scatter and absorb a fraction of the incident energy. As a result, the radiation attenuated by particulate matter is a function of the particle size, particle shape, particle refractive indices and the radiation wavelength. If the size of an illuminated particle (or the concentration of particles) is the only unknown quantity, it can be determined from detailed measurements of particle radiative extinction.

(1) Nuclear Detectors:

Unlike other types of nuclear radiation, beta ray is absorbed moderately by all common elements. Practically, the effects from particle size and shape in the beta ray attenuation are not very important. As a conquence, the beta radiation extinction by most materials is proportional to the total attenuating mass. Since air molecules and water vapour in the atmosphere also absorb incident beta radiation, all beta ray instruments extract particles from air for mass concentration measurements. These instruments are commonly called "beta gauge".

To interpret the results of beta ray attenuation by particles concentrated on a collecting surface, the Beer-Lambert Law is usually assumed. The accuracy of airborne particulate mass measured with a beta gauge is determined by the efficiency of the particle collecting method as well as the distribution of particles on the collecting surface. In the case of using filter media for particle collection, the non-uniformity and the hygroscopicity of the filter can become sources of error. However, in theory, replacing the conventional optical extinction method with the beta attenuation technique, a tape sampler can be improved considerably to indicate atmospheric particulate loading.

(2) Optical Detectors:

The optical aerosol detectors range from a simple tape sampler using a conventional broad bend light to a complex holography system using a single wavelength UV laser.

(i) aerosol transmissometers and reflectometers:

The paper tape samplers use long strips of paper or filter media advancing continuously or intermittently to collect particles from the air. The collected sample is then examined optically. This is done by comparing either light transmitted through or reflected from the particle loaded spot to that through or from an unexposed area. "Coh", coefficient of haze, is the unit used in the transmission type of samplers. One "Coh unit" is defined as the amount of collected particles which produce an optical density of 0.01.[40] Optical density is defined as $\log_{10}$ (Io/I), where Io is intensity of the incident radiation and I is intensity of the attenuated radiation. The measured results are usually expressed in "Coh unit per 1,000 ft of air". They are calculated from the ratio of transmitted light to the incident light and the sampled air volume by using the following equation.

Instrument reading (in Coh/1,000 ft of air)

$$= \left\{\log_{10}\left(\frac{\text{\%transmittance of clean filter}}{\text{\%transmittance of soiled filter}}\right) \times \left(\frac{\text{effective area (in ft}^2\text{)}}{\text{total sampled air volume (in ft}^3\text{)}}\right)\right\} \times 10^5$$

In a similar way, a commercial tape sampler which measures reflected light from collected particles uses "Soiling Index" for its measure-

ments. This instrument yields numbers between 0 and 100 with a unit of "RUDS (reflectance units of direct shade) per 10,000 linear feet". Readings from either type of the paper tape sampler are only good for some undefined indication of aerosol level without absolute meaning of particle concentration of any kind. This is mainly because the importance of aerosol light scattering (a function of particle size, shape, and optical properties) is not taken into consideration by these overly simple-minded devices.

For very high particle concentrations, e.g., in a smoke stack, some transmissometers are designed for measuring aerosol light extinction in situ. These instruments do not differ much from a tape sampler in principle. Without treating scattered light properly, they can only be used for relative indications instead of any quantitative particle concentrations.

(ii) <u>aerosol photometers and optical particle counters</u>

Scattering is a more effective mechanism than absorption in atmospheric aerosol light extinction. In addition, light of known wavelength scattered by a particle is also characterized by the particle size. There are a few instruments measuring light scattered by aerosols to estimate particle concentration and/or particle size distributions.

Light attenuation (scatting and absorption) of a small object is best described

by electro-magnetic theory. The calculation of radiation scattered by particles of size comparable to the wavelength of the incident light is a rather involved subject. The earlier work on scatting theory of small spherical particles by Mie[41] had not been carried further until recent important studies by Van de Hulst[42] and Kerker.[43] The well-developed theory shows that aerosol light scattering is the redistribution of a part of the incident radiation into different directions by the particles. The angular distribution of scattered light is mainly governed by the complex refractive index n (= n_1-in_2) and the size parameters α (= $\frac{2\pi r}{\lambda}$ where r is particle radius and λ is the wavelength of the radiation) of the particle (see Fig. 9 and Fig. 10). When particles are very small compared to the wavelength (e.g., $\alpha < 0.3$), including transparent air molecules and opaque metallic spheres, all particles behave like dipoles-in an electromagnetic field scattering light symmetrically with respect to the particle center (matching intensities for forward and backward scattering illustrated in Fig. 10). This "Rayleigh Scattering" has another important characteristic, that is, the ratio of the total scattered intensity to the incident intensity is proportional to the sixth power of the particles

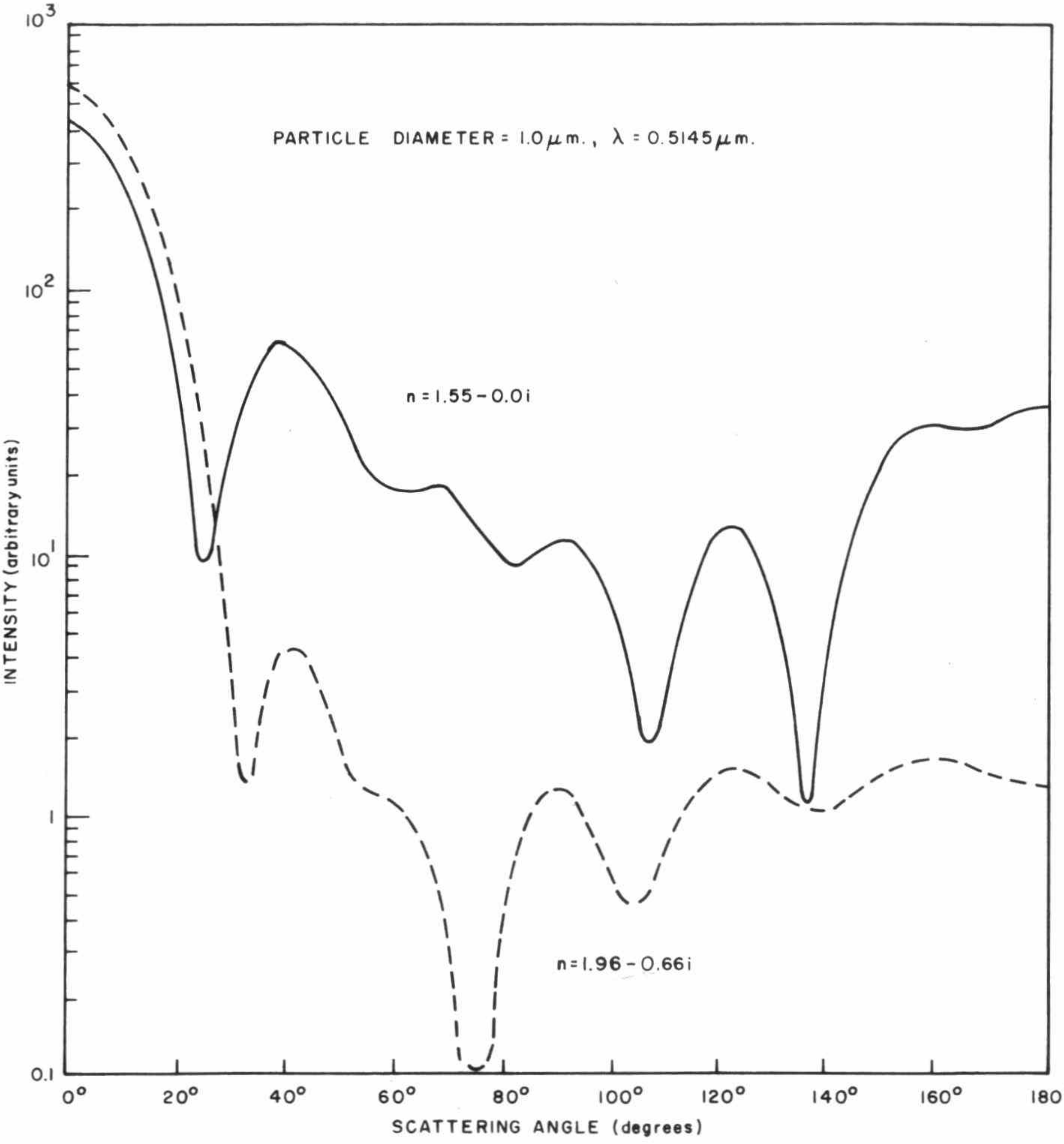


FIG. 9 SCATTERED INTENSITY AS FUNCTION OF SCATTERING ANGLE IN THE PLANE OF POLARIZATION. n = INDEX OF REFRACTION. λ = WAVELENGTH OF INCIDENT RADIATION (LINEARLY POLARIZED).

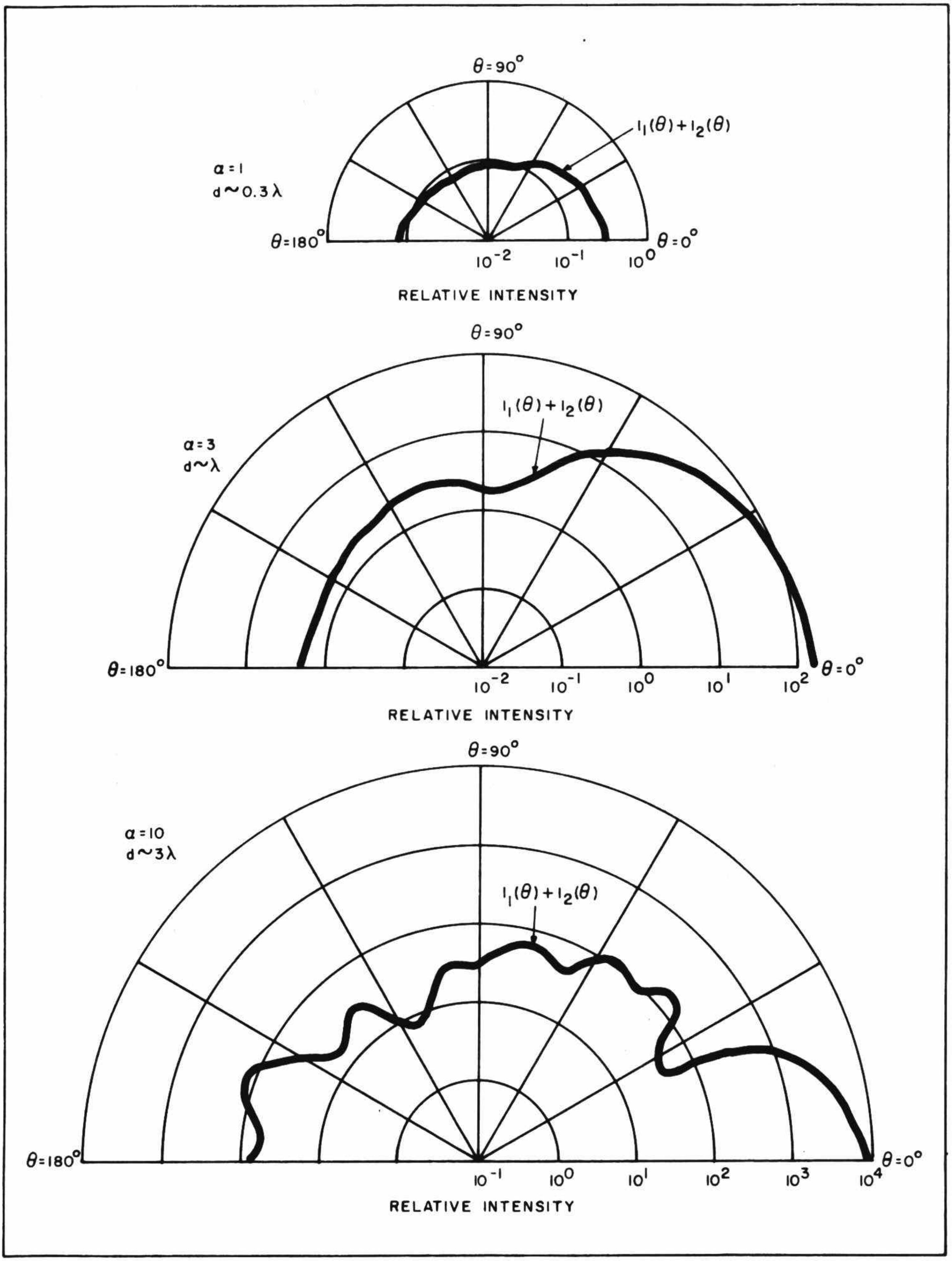


FIG. 10 LIGHT SCATTERING DIAGRAM FOR SPHERICAL PARTICLES. $I_1(\theta)$ IS POLARIZED IN THE PLANE OF THE FIGURE, $I_2(\theta)$ IS POLARIZED PERPENDICULAR TO THE PLANE OF THE FIGURE.

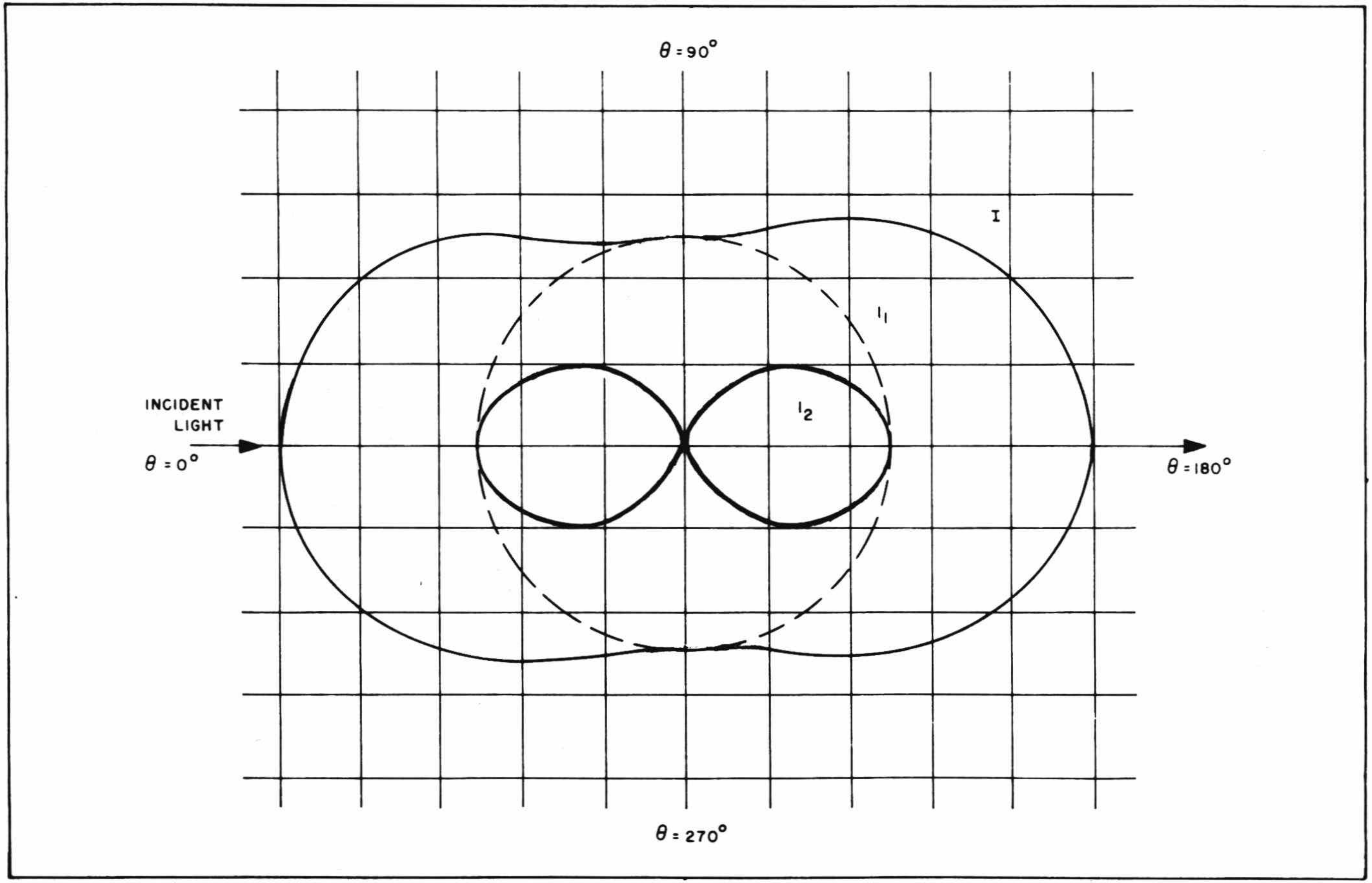


FIG. 11 RAYLEIGH SCATTERING INTENSITY I AS A FUNCTION OF THE SCATTERING ANGLE θ, I_1 IS THE SCATTERED COMPONENT IN THE OBSERVATION PLAN, I_2 IS THE COMPONENT PERPENDICULAR TO THE OBSERVATION PLAN.

radius ($\propto r^6$) and in inverse proportion to the fourth power of the incident wavelength ($\propto \lambda^{-4}$). In reality, it means that in the molecular size range, a small particle scatters far less visible light than a large one. Furthermore, it also predicts that a clean atmosphere, which is not contaminated by many particles much larger than air molecules, will scatter more short wavelength radiation than long wavelength radiation of the solar spectrum and explains why the sky appears blue.

There are significant numbers of particles in the air comparable in size to visible wavelengths. The presence of these particles reduces atmospheric visibility considerably. Mie theory indicates that the total intensity scattered by a particle in this size range is proportional to the particle volume (or $\propto r^3$) up to the size parameter α of about 5. In a small range of α between 5 and 10, large particles scatter radiation less efficiently than small particles (see Fig. 12). Eventually particles scatter incident light with a total scattered intensity in proportion to r^2 (or proportional to geometric cross section as one would expect from classical optics) when they become very large in comparison with the wavelength of the illuminating radiation ($\alpha > 30$).

Particulate matter larger than 0.03 µm in

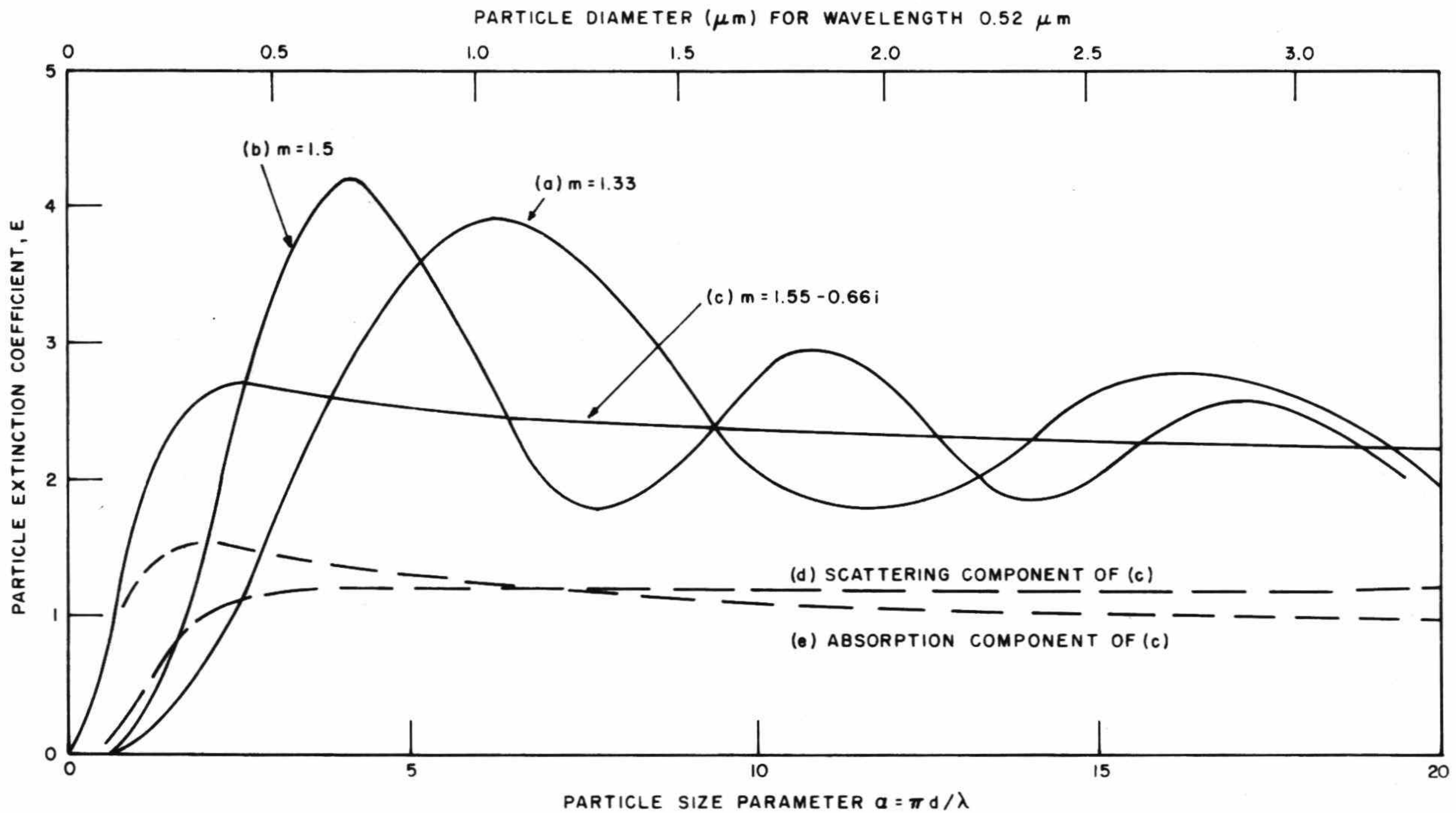


FIG. 12 PARTICLE EXTINCTION COEFFICIENT CALCULATED FROM MIE THEORY (AFTER HODKINSON[53]).

size, scatters visible light more favorably in the forward than in the backward direction (see Fig. 9). Mie scattering (light scattering by particles which have size parameter in the range roughly between 1 and 30) has a distinct angular scattering pattern (strong intensity contrast between different scattering angles). The shape of the scattering pattern is determined by the particle size parameter (α) and the intensity is dependent on both values of the particle complex refractive index ($n = n_1 - in_2$). Supposing the index of refraction is known, the size characterized angular distribution of Mie scattering would make a sensitive photometer able to estimate the size of an illuminated particle from measured scattering intensity at selected angles.

By forcing a diluted air sample to rush through a small illuminated volume, radiation scattered by any individual particle in the sampled air becomes a pulse to the light detector. Using this basic principle, an optical particle counter measures particle concentrations with respect to their size by counting the number of pulses according to their respective intensities, which correspond to different particles sizes.

Although important, it is practically impossible for an optical particle counter to determine the refractive indices (real and imaginary) of all sampled particulate matter.

These instruments, therefore, estimate particle sizes using only one assumed complex refractive index for every sampled particle. To minimize the error introduced by the deviation of particle refractive index from the assigned value, a near forward angle is often chosen. This is because the particles of interest (efficient light scatters), regardless of their refractive index, all scatter radiation mainly in a direction very close to that of the incident beam. As forward and near forward scattering intensity is not very sensitive to the change of particle index of refraction (see Fig. 9), their measurement can indicate particle size better than scattered energy at any other angles.

However, all optical particle counters give wrong results if more than one particle appears simultaneously in the viewing volume. Atmospheric particles are not usually spherical as is assumed. As a consequence, available instruments of this type may have varied performance depending upon the optical arrangement.[44]

Since the angular pattern of scattered light is a function of particle size parameter, $\frac{2\pi r}{\lambda}$, a change in incident wavelength will also change the shape of scattering pattern. Therefore, the contrast between the minimum and maximum of particle angular scattering is

greatly reduced if a multi-wavelength light source (e.g., white light) is used for illumination. Assuming that there is a light detector which is able to cover scattering angles from 0° to 180° of a small air volume, in theory, the scattered intensity measured by the detector is proportional to the total volume of aerosol particles contained in that illuminated sample. As such, a light detector requires a sensing surface of either unreasonable shape (concave hemisphere) or irrational size (infinite large). In practise, an approximation of the above conditions is usually achieved by having an ordinary radiation sensor (with a finite receiving angle) detecting light from an illuminated air tube which is specially arranged to scatter multi-wavelength incident radiation to the sensor in the near forward direction at one end, and the near backward direction at the other (see Fig. 13). Most aerosol photometers (e.g., "integrating nephelometer ") are designed according to the above-mentioned principle with some minor variations in their optical arrangement (e.g., the covered scattering angle of some instruments are rather small). Theoretically, the larger the range of viewed scattering angle, the better the instrument precision.

Aerosol photometers as well as particle

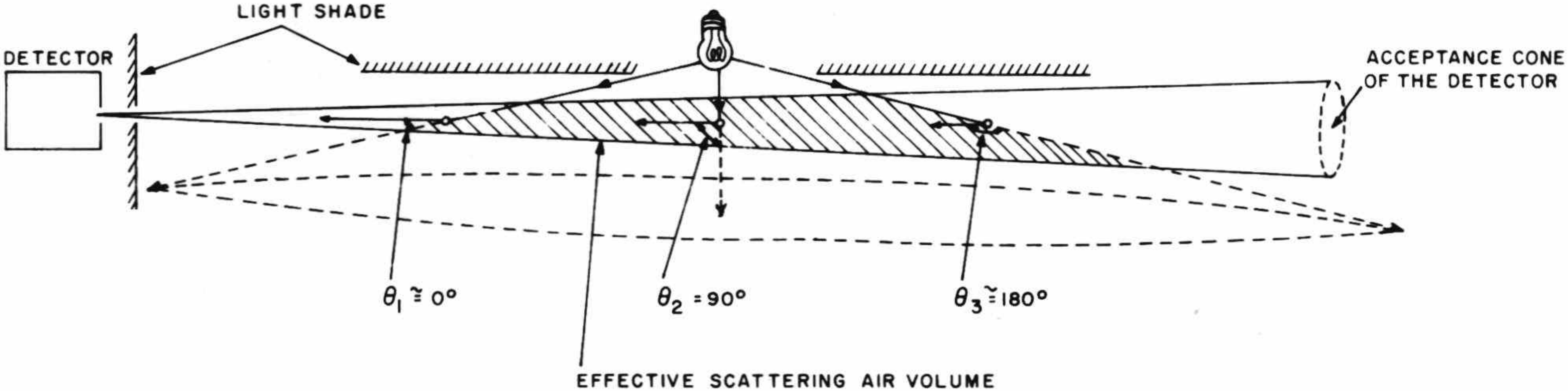


FIG. 13 OPTICAL ARRANGEMENT OF AN INTEGRETING AEROSOL PHOTOMETER-SCATTERED RADIATION WHICH IS RECEIVED BY THE DETECTOR COVERS A WIDE RANGE OF SCATTERING ANGLE θ (FROM NEAR FORWARD SCATTERING TO NEAR BACKWORD SCATTERING)

counters have limited use for measuring particles smaller than 0.2 µm in size, because of low particle scattering efficiency. Although particles stay airborne while they are detected, this technique, strictly speaking, does not allow in situ measurements. In fact, large particles (e.g., larger than 30 µm) are often excluded by the air moving mechanism of these aerosol scattering devices.

Since scattering is a function of particle volume, the instruments under discussion normally do not provide a satisfactory measurement of particle mass concentration, unless the density of the particles is known and uniform. This clearly is not the case for atmospheric measurements and thus explains why there are frequent discrepancies between results obtained by gravitational and optical techniques.

(iii) <u>condensation nuclei counters</u>:

Individual particles smaller than 0.1 µm in radius do not scatter enough visible radiation for optical detection. However, one can increase the size of these very fine particles effectively by having water vapor condense on them under suitable conditions. The condensation process usually is accomplished by saturating air with water vapor then expanding the air volume adiabatically. Light scattered from or transmitted through the fog, which is

created from the condensation of optically invisible particles (also called "Aitken nucle),[45] can then be used to measure the fine particle concentration.

All condensation nuclei counters, manual or automatic, are non-size selective instruments. They measure extra fine airborne particulate matter, from about 0.001 μm to around 1 μm in size, which is beyond the detection ability of an aerosol photometer.

(iv) <u>laser holography</u>

Magnified image of airborne particles can be reconstructed on a TV screen from the hologram of particles which are illuminated with coherent laser light pulses. The holographic instruments can size many particles simultaneously with a very large depth of field. Current commercial holographic units are able to measure particles from 0.3 μm to about 100 μm. They "scan" aerosols in situ without disturbing particles by any means. Particulate matter moving with very high speed (up to about 100 m/sec) can be "frozen" by very fast laser flashs ($\simeq$ 20 ns/pulse).

Nevertheless, manual analysis of a hologram is a very time consuming process. An automatic hologram analytical system needs a minicomputer and thus increases the cost of this

technique even further.

(b) Summary and Comments:

By adopting the beta radiation extinction technique, a tape sampler yields more meaningful results than that obtained with an optical detector (Coh devices). With some limitations, optical photometers and particle counters are still valuable instruments for measuring volume concentrations of airborne particulate matter in the 0.1 µm to 10 µm range. Condensation nuclei counters are not particle sizing devices but are very useful for total particle counts in the submicron range. Holography is a new method for large particle detection in the laboratory. Holographic systems are not feasible for use in the field because of size and cost considerations.

D. AEROSOL PRECIPITATORS

Instruments using electric fields or thermal gradients to collect suspended particles from sampled air are commonly called precipitators. Compared to mechanical aerosol separating processes such as impaction and filtration etc., precipitation forces exerted on aerosol particles are very gentle and more efficient. Theoretically, precipitators are able to remove particles of all sizes from air.

(a) Instrumental Principles and Operational Suggestions:

The precipitation of aerosols usually involves drawing a sample into a confined space. Particles are then treated and forced to deposit onto a collecting surface under an artificial environment.

(1) Electrostatic Precipitators:

Utilizing one electrode to charge aerosol particles, another (of opposite polarity) to collect them, an electrostatic precipitator maintains avery large potential difference inside the instrument. A fraction of the atmospheric aerosol particles are charged by various complicated processes. Since normally there is a random distribution of electric charge (both positive and negative) on atmospheric particulate matter, all electrostatic precipitators impose charge on particles for efficient collection. Unipolar charging of particles by the slow procedure of radioactive ionization sometimes is desirable. How-

ever, corona discharge has been widely adopted by most commercial precipitators because of its efficiency and rapidity. This process usually involves a high voltage discharge of a thin wire through ionization of nearby air molecules.

After acquiring an electrical charge, particles are attracted and collected by a high potential plane electrodes of reverse polarity. For size analysis, charged particles are often deposited directly on electron microscope grids. This will avoid unnecessary processing of the collected sample and yield more accurate results.

A direct reading electrostatic precipitator has been developed recently for fast aerosol mass concentration measurements.[(46)] In this instrument, particles are precipitated onto a piezoelectric micro-balance sensor. Nevertheless, these devices are still in the developmental stage and, not yet suitable for ambient aerosol measurements.

Among the limitations of electrostatic precipitators, a couple are worth mentioning:

(i) they require relatively stable sampling environmnet (humidity and temperature in particular) (ii) sampled air cannot contain explosive mixtures.

(2) Thermal Precipitators:

The higher the temperature of gas, the faster the movement of its molecules. Particles suspended in air of uneven temperature tend to migrate from the warm end to the cool because of the unbalanced bombardment of air molecules. Theoretically, with an appropriate collecting surface at the cool side of a significant thermal gradient, all submicron airborne particles can be collected. The collection of large particles by a thermal precipitator is only limited by problems of upstream losses.

In practise with an actual system, air is slowly drawn into a thermal chamber. A suspended hot wire (or plate) is often used to drive and deposit particles onto a cooled glass slide or metal surface. The particle collection efficiency of thermal precipitators is very high but they are not suitable for sampling volatile particulate matter. A very small sampling flow rate is a serious limitation of all thermal precipitators.

(b) Summary and Comments:

Electrostatic and thermal precipitators have very high collection efficiencies for aerosol particles between 0.01 µm and about 10 µm in size. Electrostatic precipitators are often favoured because of its greater sampling speed. On the

other hand, for some special applications, a thermal precipitator may become the only choice because its particle separating force is so gentle that aerosols can be sampled without fracturing fragile particles.

Both positive and negative corona discharge are used to charge particles in commercial electrostatic precipitators. If the presence of ozone, a by-product of high voltage discharge, is not desirable, an instrument utilizing positive corona is a better choice.

E. MISCELLANEOUS PARTICLE SIZE ANALYSERS

There are commercial instruments making use of basic techniques which are not discussed in the previous sections because of their limited use or unusual complexities. For the sake of completeness, two relatively important types of particle sizing devices will now be described. These are the simple gravitational instruments and the complicated ion mobility analyser.

A gravitational particle elutriator classifies particles according to their falling speed in air. Since the suspended liquid or solid particulate matter has a much higher density than air, if there are no other perturbing forces, all particles settle down slowly due to gravitational attraction. The resistant force acting on the falling particles increases very rapidly with increasing particle speed. The balance of the gravitational acceleration and the resistant force from air causes particles eventually to fall with a constant speed, terminal velocity, which is determined mainly by the particle size and density. A horizontal elutriator is a typical commercial version of gravitational aerosol equipment which uses horizontal parallel plates to collect falling particles while slow air streams are forced to flow through the gaps between plates. Since these devices use one assumed mass density for all collected particles, they are particle classifiers rather than particle analysers. Obviously, the sampling rates of these elutriators are extremely low and as well they have no practical use for submicron particles.

Ion mobility analysers, which are developed from the concept of electrostatic precipitation, estimate the aerodynamic size of charged particles by measuring their mobilities in a known electric field.

Theory indicates that the amount of charge acquired by suspended particles from a homogeneous cloud of ions is proportional to the particle size. However, since the particle mass is in proportion to the cube of the particle radius, smaller particles have a higher electric mobility after they are charged by homogeneous ions.[47] Various experimental and operational research has resulted in a series of modified instruments for submicron particle analysis[48] using ion mobility as the separating mechanism.

The latest version of an ion mobility analysing system imposes electric charges on particles in a diluted air sample by means of positive corona discharge. In the analysing section of the instrument, charged particles are attracted to a long metal rod with an adjustable negative voltage. It is apparent that only particles smaller than a certain size (which have electric mobilities larger than a critical value) will be collected by the rod when a corresponding negative voltage is applied. Large particles which escape precipitation from the rod are captured downstream by a current collecting filter. The concentration of these large particles is indicated by an electrometer connected to the filter. Therefore, step changes in the rod voltage of the instrument gives discrete readings on the electrometer. The difference between two consecutive readings is then converted by the analyser (pre-calibrated with laboratory aerosols) to a particle concentration between two particle sizes.

The principle of particle mobility instruments is sound in theory. They have demonstrated their unique value for sizing submicron particles of wide range in real-time.

However, the most recent commercial ion mobility analyser has been available for less than three years with a very limited number of users. An extensive calibration of each of these instruments by other existing techniques is absolutely necessary for obtaining reliable results. Moreover, these electric particle counters are extremely complicated and expensive. A knowledgeable operator is essential for the use of these devices.

V. SUMMARY AND CONCLUSIONS:

Particulate matter suspended in air has very significant meteorological and health effects. The concentration, size distribution, chemical composition, and physical properties of aerosol particles in the atmosphere varies from time to time and from location to location. Given the present state of the art, no single technique is adequate for sampling atmospheric airborne particles covering the entire size spectrum.

In inhabited areas, secondary aerosol particles (those not emitted directly), are mainly contributed by human activities, and are submicron in size. They are respirable and thus can be a serious health hazard. Measurement of the respirable particulate matter alone provides a more sensitive indication of our ambient air quality, than does the total mass loading of atmospheric particulate matter.

Because all existing aerosol measuring techniques have their practical limitations, careful selection of instruments for each individual application is very important. The accuracy of results measured by most aerosol devices depends on the calibration of the instrument using artificial particles. However, particulate matter in the atmosphere is a constantly changing mixture of particles with diverse chemical and physical properties. Due to the lack of a standard atmospheric aerosol, the artificial particles used to calibrate instruments by manufacturers are usually different for different instruments. The characteristics of these simulated aerosols can also be very different from those of the atmospheric aerosols that are to be measured at the sampling site. Therefore, if accurate measurements are required, aerosol instruments should be re-

calibrated by the operator with the appropriate particles, according to the instrumental principles involved, and the actual sampling conditions. In addition, if more than one instrument is to be used for the same application, all aerosol devices should be calibrated with the same type of particles to yield meaningful results.

Although it is clear that no currently available general purpose instrument can be recommended for monitoring the various aspects of particulate matter in ambient air, recently, there seems to be increasing demand for multi-stage inertial particle collectors, (e.g., cascade impactor heads for "Hi-Vol" samplers and virtual impactors) and integrating aerosol photometers. It may indicate that the actual effects of atmospheric particles (e.g., visibility reduction and potential adverse health consequences) are receiving greater consideration when users select their aerosol monitors. Probably, it can be expected that this may become a trend for the development of new commercial instruments in the future. However, it would be premature at this time to state that a trend has been developed.

Now, a concise discussion of different instrumental principles has been presented. Table 3 summarizes the usefulness of each measuring technique for airborne particles in various size ranges. Brief individual descriptions of major commercial instruments utilizing the discussed principles will then be presented.

TABLE 3. INSTRUMENTS FOR SAMPLING AIRBORNE PARTICLES IN DIFFERENT SIZE RANGES

Particle Size Range	Effects	INSTRUMENTS		Remarks
		Type	Is it Size Selective ?	
$0.01\ \mu m \lesssim r \lesssim 0.5\ \mu m$	1. greater health hazard 2. cloud nucleation	Ion mobility analyser	Yes	Expensive, bulky, lab instrument only.
		CN counter	No	Measuring particle volume concentration; portable; manual units do not require power supply; suitable for field use.
		Electrostatic precipitator	Can be	Samples taken by both precipitators can be examined with optical and electron microscopes for particle size information.
		Thermal precipitator	Can be	
$0.3\ \mu m \lesssim r \lesssim 10\ \mu m$	1. visibility reduction 2. health hazard (especially small particles) 3. precipitation effects.	Optical particle counter	Yes	Practical instrument but the meaning of results obtained need careful interpretation.
		Aerosol photometer (or Nephelometer)	No	Fair correlation between the measured visibility and the particle mass concentration.

TABLE 3. INSTRUMENTS FOR SAMPLING AIRBORNE PARTICLES IN DIFFERENT SIZE RANGES (Cont'd)

Particle Size Range	Effects	INSTRUMENTS		Remarks
		Type	Is it Size Selective?	
$r \gtrsim 0.3$ µm	dependent on the composition and size but includes: 1. visibility reduction 2. corrosion 3. soiling	Filter sampling system	Can be	The actual size range is determined by the filter media in use.
		Cyclone	Can be	Sample can be analysed subsequently.
		Laser holography	Yes	Expensive, lab. use only
$r \gtrsim 1.0$ µm	dependent on the composition and size but including: 1. corrosion 2. soiling, etc.	Impactor	Yes	Does not have sharp cut-off size; impinger has only limited use for particle sizing.
		Impinger	Yes	
		Gravitational elutriator	Yes	

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VII. DESCRIPTION AND COMMENTS ON SELECTED AEROSOL INSTRUMENTS

A. Filter Sampling Systems: High-Volume Samplers

High-Volume Samplers:

Uses: particle collection for the measurement of loading and composition of collected material

Basic Principle: Filtration

Particle Size Classification: No (possible with attachment)

Particle Size Range: 0.01 μm to 100 μm

Particle Concentration Range: down to about 10 $\mu g/m^3$ for practical use

Particle Collection: Yes

Flow Rate: 20 to 60 ft^3/min

Power: Standard a.c. (d.c. powered units are also available)

Dimensions and Weights: 10" (w) x 10" (l) x 10" x (h); 10 lbs to 20 lbs. variable from different manufacturers

Description and Comments:

The "Hi-Vol" sampler is a common name for the commercial filter system using a high speed air blower (with a typical flow rate of 40 to 60 cfm for clean glass fiber filter) to collect airborne particles on a large piece of high-efficiency filter (normally 8" x 10" in size) held in an open-faced filter holder. The use of a "Hi-Vol" sampler for measuring total suspended particulate matter in ambient air has been adopted as the standard method by U.S. Environmental Protection Agency since 1971. A "Hi-Vol" is usually operated for a 24 hr sampling period in outdoor environments. Recently, it also has seen increasing use in occupational settings. NASN (National Air Sampling Network) "Hi-Vol" samplers are those utilizing 8" x 10" filters and have some type of outdoor shelter to meet the specifications of U.S. Public Health Service.

Glass fiber is the most commonly used filter medium with "Hi-Vol" samplers because of its high collection efficiency and its small hygroscopicity. Some other filter media, e.g., Nuclepore filter, are also available for special applications such as sampling of asbestiform fibres.

The large quantities (200 mg) of suspended particulate matter that can be collected for subsequent analyses is an important advantage of using the "Hi-Vol" method for ambient air sampling.

The assumption of a linear decrease in sampling flow rate often introduces a significant error in the estimate of the volume of air sampled. Since the ambient particle concentration can vary over a wide range during entire sampling period of 24 hr., a constant flow controller sensing either the pressure difference across an orifice or the entire air mass flow is recommended to regulate the motor speed of the sampler.

For large volume, crude size fractionating sampling, there are some cascade impactors specially designed for the use with a basic "Hi-Vol" sampler. These attachments are described in the section of "Inertial Particle collectors". Some of these impactors can split the suspended particulate matter into two fractions; respirable (≤ 4 µm) and non-respirable (>4 µm).

There are choices of "Hi-Vol" sampler available from various manufacturers. Major commercial units are summarized in Table 4.

TABLE 4 : Commercial "HI-VOL" Samplers

Name and Model	With Shelter or Portable	Required Power*	Price (1976)	Supplier	Remarks
Bendix 550	P	a.c. or 24V d.c.	475	National Environment Instrument	
Bendix 500	S	a.c.	780		NASN
BGl Hi-Vol	S	a.c.		N.S. BGl Inc.	NASN
BGl Universal Hi-Vol	P		99	Canada: Hoskin Scientific Ltd.	4" diameter filter holder can adopt 8" x 10" head.
GII Super Vol "500"	S	a.c.	440	GII Interprises Inc.	Useable from 20 to 30 ft^3/min
General Metal W 2000 CM	S	a.c.	320	U.S. General Metal Works	
General Metal W 2000 HCM	S	a.c. or d.c.	650	Canada: Levitt Safety Eastern Limited.	NASN W 2000 CM + timer + recorder etc.
Hoskin "Hi-Vol"	S	a.c.	300	Hoskin Scientific Ltd.	NASN
Misco Model 2000	P	a.c.		Misco Scientific Ltd.	Model 8000 is a compact version of Model 2000 with an option of 24V d.c. motor.
Misco Model 620	S	a.c.			
Sierra Hi-Vol Model 305	S	a.c.	225	U.S.: Sieera Instruments Incorporated. Canada: Applied Research Products Ltd.	

* 115 V a.c. 60 Hz is the standard for all a.c. power

B. Inertial Particle Collectors.

(1) Impactor Heads for "Hi-Vol" Sampler:

Use: Particle sizing while sampling with a "Hi-Vol" Sampler

Basic Principle: Inertial Separation and Impaction

Particle Size Classification: Yes

Particle Size Range: See individual description.

Particle Concentration Range: Concentration of ambient air or higher.

Particle Collection: Yes (on impaction substrate)

Flow Rate: 20 to 60 ft^3/min

Power: No additional power is required when used with a "Hi-Vol" sampler

Dimensions and Weight: See individual description.

Description:

Andersen Hi-Vol Fractionating Sampler:

Model 65-000:

Type of "Hi-Vol" sampler: all GMW Hi-Vol sampler

Number of Stages: 4, plus 1 backup filter

50% particle cut-off size:

Stage	Diameter
1	7.0 µm
2	3.3 µm
3	2.0 µm
4	1.1 µm
Backup Filter	0.01 µm $< d <$ 1.1 µm

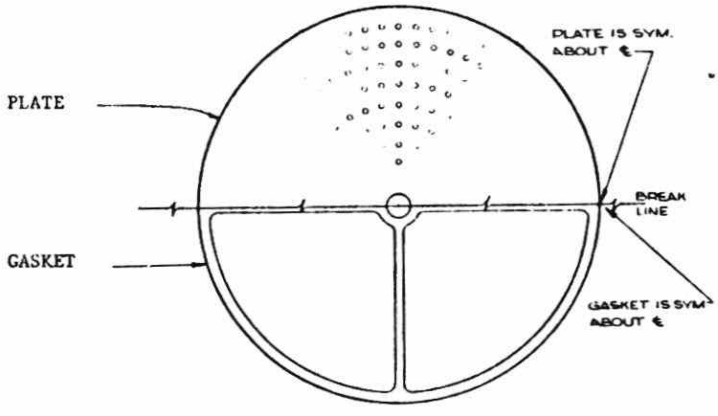
Standard Collection Surface and Filter Media: Type A glass fiber filter.

Flow Rate: 20 ft^3/min

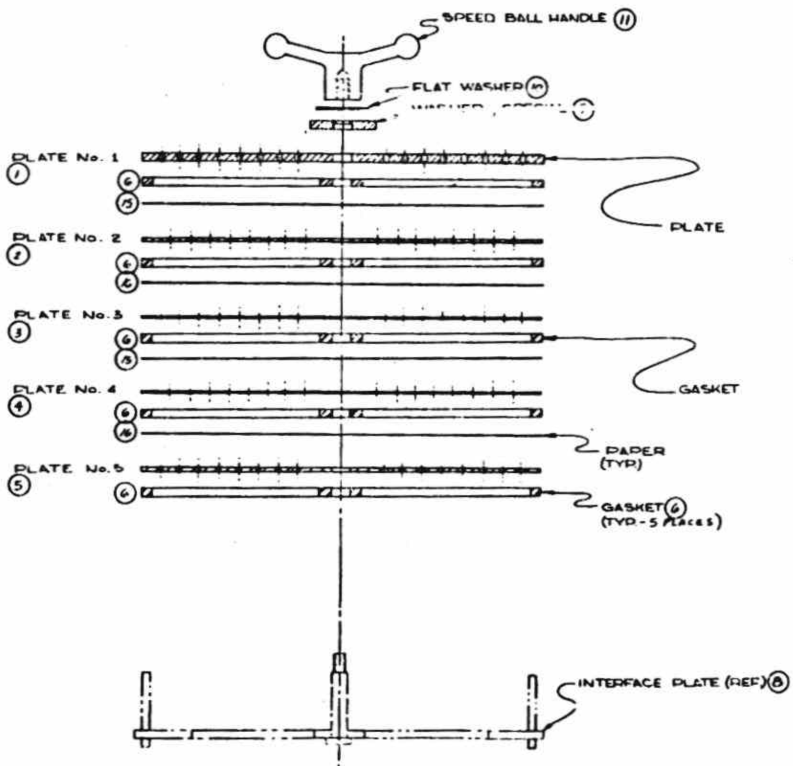
Dimensions: 12.25" (dia.) x 5" (h)

Price as of late 1975: $600 in U.S. - $660-$750 in Canada (1976)

This "Hi-Vol" attachment is a multi-stage, multi-jet cascade impactor made of circular aluminum plates separated by rubber gaskets (see Figure 14). Each plate contains 300 small holes of the same size. The diameter of the holes reduces in steps from top to bottom plates. Particles are deposited according to their aerodynamical size on 4 round filter papers sandwiched



HALF VIEW OF PLATE AND GASKET



ILLUSTRATIVE SECTION

FIG. 14: ANDERSEN HI-VOL FRACTIONATING SAMPLER

between plates. Small particles which escape impaction are collected by a 8"x10" backup filter of the basic "Hi-Vol" Sampler.

Model 66-000:

The Model 66-000 is identical to 65-000 but is designed for adoption to Misco "Hi-Vol" Sampler,

Model 68-000:

Number of Stage: 2 stages plus 1 backup filter.

50% particle cut-off size:

Stage	Diameter
1	7.0 µm
2	1.1 µm
Backup Filter	$0.01\ \mu m < d < 1.1\ \mu m$

Flow Rate: 20 ft^3/min

Price as of late 1975: $400 in U.S.

The Model 68-000 is the 2 stage version of the Model 65-000

Model 69-000:

Number of Stages: 1, 1 backup filter

50% particle cut-off size

Stage:	Diameter
1	3.5 µm

Backup Filter: $0.01\ \mu m < d < 3.5\ \mu m$

Flow Rate: 40 ft^3/min

Price as of late 1975: $300 in U.S.

This is the single stage version of the Model 65-000.

Supplier (all above Models):

U.S. - Andersen 2000 Inc.

Canada - (1) Hoskin Scientific Ltd.

(2) Levitt Safety Eastern Limited.

User's Comments:

" 'Type A' 8" x 10" glass fiber webs normally used are quite alkaline (pH $\approx$ 11.0) and it was ascertained that particulate formation resulting from acid gas reactions caused erroneously high mass loadings on the Andersen's. It is suggested that sampling can be conducted with a near neutral glass fiber" (pH $\simeq$ 7).

"Collection efficiency decreases with smooth collection surfaces e.g., Aluminum Foil".

"The Andersen Head could be substituted for the standard Hi-Vol Sampler without changing the data base. It provides information regarding particle size which is consistant with what the manufacturer specifies as the size range for the various stages of the Andersen Head."

BG1 - 30 Hi-Vol Cascade Impactor:

Type of "Hi-Vol" Sampler: Fits any "Hi-Vol" sample if specified.
Number of Stages: 4, with 1 Backup filter
Collection Characteristics: See Figure 15
Standard Collection Surface and Filter Media: Glass Fiber
Flow Rate: 30 ft^3/min
Price as of late 1975: \$380 in U.S. \$413. in Canada
The 4-stage impactor has a slit at the center of each plate. Particles are separated into 5 fractions and collected on 2" x 5" fiberglass filter sheets (Stage 1 to 4) and a 8" x 10" backup filter on the standard "Hi-Vol"
Supplier: U.S. - BG1 Inc.
Canada - Hoskin Scientific Limited
User's Comment:

"Standard glass fiber filter for this impactor has high pH value, therefore is not suitable for sampling acidic aerosols".

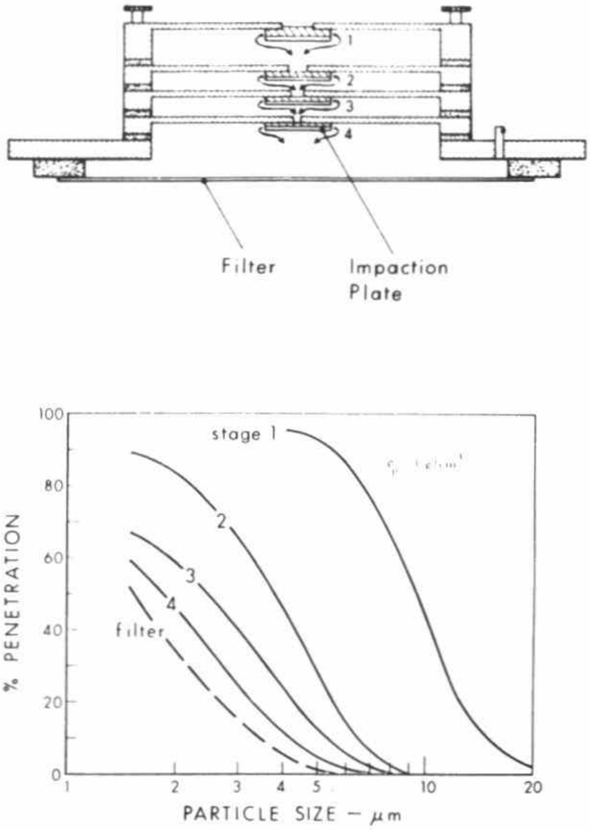


FIGURE 15: BGI 30 HI-VOL Cascade Impactor and its Collection Curves

"Use of membrane filters with this impactor is difficult in loading and unloading".

Sierra Hi-Vol Cascade Impactor 230 Series:

Type of "Hi-Vol" Sampler: All standard "Hi-Vol" samplers

Number of Stages: 1 to 5 stages with a "Hi-Vol" backup filter

50% particle cut-off size (40 cfm, 25°C; 75 C, Hg; unity specific gravity of particles).

Stage	Diameter
1	7.2 μm
2	3.0 μm
3	1.5 μm
4	0.95 μm
5	0.49 μm
"Hi-Vol" Filter	< 0.49 μm

Standard Collection Media: Slotted, glass fiber filter paper

Flow Rate: 20 to 60 ft^3/min

Dimensions: Model 235 - 9.25" (w) x 12" (L) x 2" (h)

Weight: Model 235 weighs roughly 5.5 lbs

Price as of late 1975: $ 725. in both U.S. and Canada

This series of impactors provides a choice of a 1 to 5 stage, cascade, multi-slit, aluminum sampling head (see Figure 16). They are designed to classify particles of 0.49 um and larger in outdoor and occupational environments. Particles are sized and collected on 5.375" x 5.625" slotted, Type A glass fiber filter.

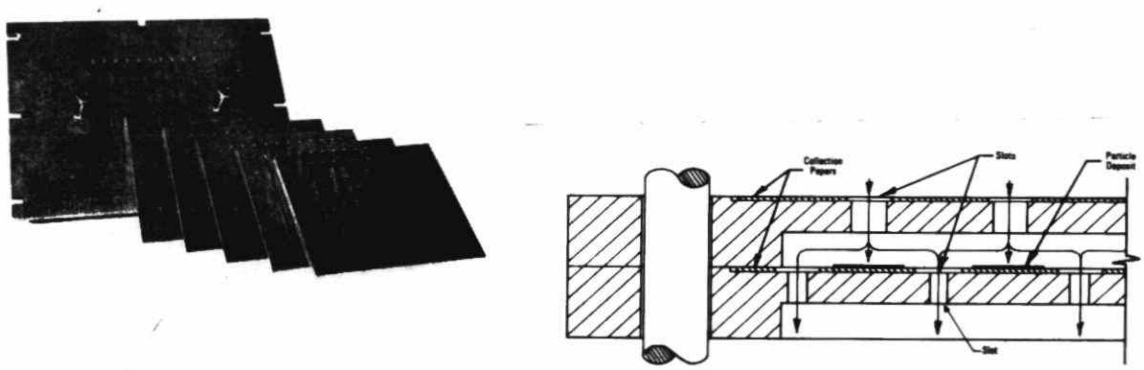


FIGURE 16: Sierra Hi-Vol Cascade Impactor

The Model 235 has all five stages while the Model 234 has Stages Nos. 1,2,3, and 4. The Model 231 R consists of only No. 2 impactor stage of the Model 235 and is for separating coarse particles from respirable dusts with a cut-off size near 2.5 μm.

Supplier: U.S. - Sierra Instruments Incorporated

Canada - Applied Research Products Limited

User's Comments:

"The actual performance may vary considerably from instrument to instrument." "All these "Hi-Vol" attachments (including Andersen, BGl,

and Sierra) have particular difficulties in their individual performance; by comparing them side by side, we do not find that any one of them is obviously superior to the others, therefore, we cannot recommend any one of these sampling heads over the other for standard network sizing equipments."

(2) Single Stage Impactors:

MRl Model 1500 Moving Slide for Impactor:

Use: Sampling suspended particles in polluted air

Basic Principle: Inertial Impaction

Particle Size Classification: No (Particle size can be analysed with a microscope)

Number of Stages: 1

Particle Size Range: 0.1 μm or larger

Particle Concentration Range: typical ambient air concentration

Particle Collection: Yes

Collection Media: Microscope slides

Power: 115 Vac, 50/60 Hg: 250 Watts

Dimensions: 8" (w) x 17" (d) x 11" (h)

Weight: 28 lbs

Description:

This portable instrument uses two identical impactors to collect airborne particles on microscope slides simultaneously. The impactors can be programmed to sample air automatically at various deposit densities on different sections of the same slide to insure that samples will be adequate for microscopical examination.

Supplier: U.S. - Meteorology Research Incorporated.
Canada - Carleton Instrument Limited

Sartorius Konimeter:

Use: particle sampling in the occupational environment for microscopical examination

Basic Principle: Inertial Impaction

Particle Size Classification: particle size can be evaluated with the attached microscope

Number of Stages: 1

Particle Size Range: 0.7 µm to 5 µm

Particle Concentration Range: Designed for high particle concentrations up to 2,000 particles/cm^3

Particle Collection: Yes (36 samples on each collection disc)

Sample Volume: 2.5 or 5 cm^3

Collection Media: Glass Disc

Power: Hand Operated

Dimensions: 4" (dia) x 10" (h)

Weight: 31 lbs (1410 g)

Description:

The Konimeter is a light weight impactor for sampling dust particles in factories and mines without the use of electric power. Samples are collected on a glass disc with a small steel piston pump and are then examined with an attached 200 X microscope. The impactor of the instrument uses a single conically shaped jet to accelerate particles for impaction.

Supplier: Europe - Sartorius-Membrane filter GmbH
Canada - BDH Chemicals Canada Limited

User's Comments:

"The results of the Konimeter do not co-relate well with the results of the standard "Hi-Vol" sampler, probably due to the fact than an impactor can not collect very fine particles."

(3) Multi-Stage Impactors:

Andersen 1 CFM Ambient Sampler 20-000 and 10-000 Series

Use: In-plant sampling

Basic Principle: Cascade Inertial impaction

Particle Size Classification: Yes

Number of Stages: 20-000 Series: 8 10-000 Series: 6

50% Particle Cut-off Size (20-000 series at 1 cfm)

Stage	Diameter
1	11.0 µm
2	7.0 µm
3	4.7 µm
4	3.3 µm
5	2.1 µm
6	1.1 µm
7	0.7 µm
8	0.4 µm
Back up Filter	0.05 µm $<$ d $<$ 0.4 µm

Particle Size Range: 20-000 Series - 0.05 um and larger

10-000 Series - 0.65 um and larger

Particle Concentration Range: Concentration of occupational environment.

Particle Collection: Yes

Flow Rate: 1 ft^3/min

Collection Media: Glass or Metal Plates

Power: Choice of 115 Va.c., 230 Vac or 12 V.d.c.

Dimensions: 20-000 Series - 9.75" (w) X 5" (d) X 8.75" (h) with case

Weight: 20-000 Series - 6.25 lbs without pump; 18.25 lbs with a.c. pump

19.75 lbs with d.c. pump

Description and Comments:

The basic Andersen Non-Viable Sampler (20-000 Series) consists of 8 aluminum stages which are held in position by 3 spring clamps. Each stage of the impactor contains 400 orifices whose diameters get progressively smaller from top to the bottom stages, ranging from 0.0625 to 0.0100 inches. Each stage has a glass or metal collection plate slightly smaller than that stage to allow for continuous air flow (see Figure 17). An 81 mm backup filter for the collection of submicron particles is optional. The sampler can be purchased with choice of three different pumps. The 21-000 package includes a 20-000 sampler described above and a 115 Va.c.; 50/60 Hz motor. The 22-000 model specifies a basic sampler and a 220/240 Va.c. pump. If a 12 Vd.c. air mover is desired, the 23-000 should be ordered.

The 10-000 series offers similar samplers except they are slightly smaller in size. This series is designed for sampling particles larger than 0.65 μm in 6 stages and is named Andersen viable sampler.

Regardless of the type of the pump, periodic adjustments of a valve on the pump to maintain a constant air flow rate of 1 cfm while sampling is required for a good particle size classification by Andersen Samplers.

Price as of late 1975: 20-000:$1,145. 10,000 Series: $975.

Suppliers:

U.S. - Andersen 2000 Inc.

Canada - (1) Hoskin Scientific Limited

(2) Levitt Safety Eastern Limited

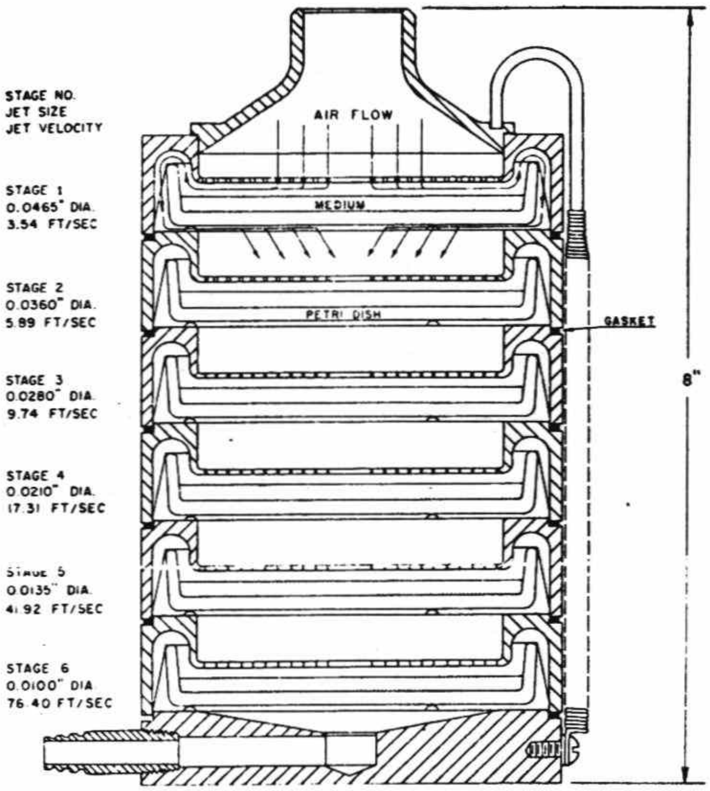


FIGURE 17: Cross-Section of Andersen Sampler 20-000 Series

Casella Cascade Impactor Mk 2g:

Use: Ambient sampling of particles including volatile droplets

Basic Principle: Inertial Impaction

Particle Size Classification: Yes

Number of Stages: 4, plus a backup filter if desired.

Particle Collection Characteristics: See Figure 18.

Particle Size Range: 0.5 μm to 50 μm

Particle Collection: Yes

Flow Rate: 0.62 ft^3/min (17.5 liters/min)

Collection Media: Glass discs

Power: 115 Va.c.; 60 Hz; 40 Watts

Dimensions: 4.5" (w) x 2" (d) x 5.5" (h)

Weight: 2 lbs.

Description:

Air is drawn into the instrument through a series of 4 jets which are at right angles to each other. After each of the four jets, particles are collected onto a glass disc of 25 mm diameter for microscopical examination. A backup filter can be added as fifth stage to collect particles smaller than 0.5 um. The impactors can be separated so that any of the four stages can be used independently. An oil-less pump (not included) capable of drawing 17.5 liters per minute of air at 3 inches of mercury is recommended for these impactors.

Price as of late 1975: $110 F.O.B. Waltham, Massachusettes

Supplier: U.S. - BGI Incorporated

Canada - Carleton Instruments Limited

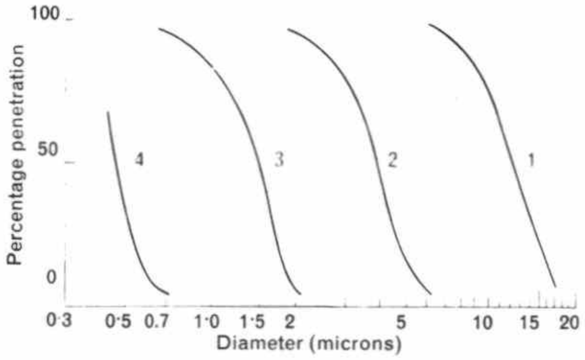


FIGURE 18: Penetration, for Spheres Density 1.0 at Flowrate of 17.5 Litres/Min; 1. First Disc; 2. Second Disc 3. Third Disc; 4. Fourth Disc.

<u>Lundgren Impactor Model 4220 Series and Multi-Day Impactor Model 4620 Series</u>:

Uses: Sampling solid particles and/or liquid droplets in terms of size and time.

Basic Principle: Cascade Inertial Impaction

Particle Size Classification: Yes

Number of Stages: 4220 - 4, plus 1 backup filter

4620 - 2, plus 1 backup filter

50% particle Cut-off Size:

Stage	Diameter (4220)*	Diameter (4620)**
1	10 μm	5 μm
2	3 μm	0.5 μm
3	1 μm	
4	0.3 μm	

* 4 cfm; 3 inches of Hg; Special gravity of particles = 2

** 1 cfm; Special gravity of particles = 1

Particle Collection: Yes

Flow Rate: 3 to 5 ft^3/min

Collection Media: Mylar or Teflon Sheet

Power: Model 4220 A - 115 Va.c.; 60 Hz; 5 Watts

Model 4220 B - 115 Va.c.; 60 Hz;10 Watts

Model 4620 - 115 Va.c.; 60 Hz;75 Watts (0.1 hsp)

Dimensions:

Model 4220 A - 20" (w) x 4" (d) x 6" (h)

Model 4220 B - 21" (w) x11" (d) x 8" (h)

Model 4620 - 16" (w) x13" (d) x 11.5" (h)

Weight:

Model 4220 A - 14 lbs.

Model 4220 B - 30 lbs.

Model 4620 - 25 lbs.

Description:

The Model 4220 A is a basic Lundgren Impactor which consists of 4 impaction stages. Each stage of the impactor uses an aluminum drum of

10 square inches to collect impacting particles. The drums rotate slowly at a speed of 1 revolution per day for the indication of particle variation during the sampling period.

The instrument accelerates air with converging nozzles of successively reduced slit width (see Figure 19). Since the speed of the air jet is increased from stage to stage, the size of particles deposited is reduced from drum to drum.

The Model 4220 B consists of a flowmeter, a backup filter holder, a field-type case and an impactor identical to Model 4220 A, except that the drum speed is variable from one revolution per minute to one revolution per day.

With a similar design, the Model 4620 offers a 2 stage impactor equipped with a dequential after filter (47 mm). The rotating collection drum in the impactor are driven by a gear train to complete one revolution every eight days. The Model 4620 C contains the model 4620 impactor and a flow controller. A constant flow rate is selectable from 0.5 to 1.0 standard cubic foot per minute for this model.

For all of the above impactors, Mylar (4222) and Teflon (4223) collection substrates are available from the manufacturer.

Price as of late 1975: 4220 B- $2,750.

Supplier: U.S. - Sierra Instrument Incorporated

Canada - Applied Research Product Limited

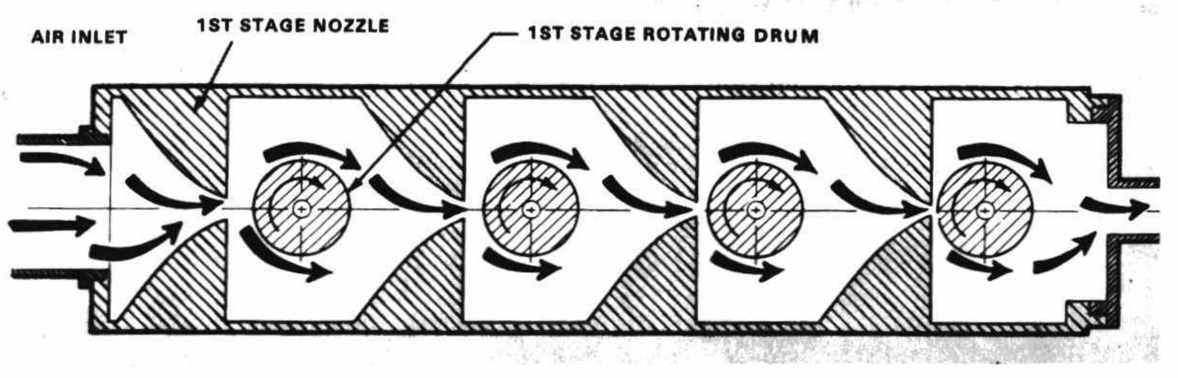


FIGURE 19: Lundgren Impactor Model 4220 A

RAC Suspended Particle Fractionating Sampler:

Use: Size segregative sampling of particles in ambient air

Basic Principle: Inertial Impaction

Particle Size Classification: Yes

Number of Stages: 5, plus 1 backup filter

50% Particle Cut-off Size: from 3.0 µm (1st stage) to
0.5 µm (5th stage) dia.

Particle Collection: Yes

Flow Rate: 4 to 5 ft^3/min

Collection Media: Aluminum foil disc

Power: 115/230 Va.c.; 60 Hz;
7.8 amp at 115 V.; 3.9 amp at 230 V

Dimensions: 16.5" (w) x 12.5" (d) x 46" (h) in operation

Weight: 90 lbs.

Description:

This sampler has a cascade impactor standing on a control unit enclosed in an 18 gallon shelter. The impactor has a design similar to that of the Andersen 10-000 sampler and the air inlet is approximately 3.125" in diameter. There are 400 jet orifices on each stage and their diameter are progressively smaller from the top to bottom stages ranging from 0.0465" to 0.0135". Each stage has a stainless steel plate of 3.25" to support an aluminum foil disc of the same size for particle deposition.

Normal particle segregation of this sampler ranges from about 3.0 µm to 0.5 µm dia. Particles small enough to escape final stage impaction are collected downstream by a backup filter. Either glass fiber or membrane filters of 4" dia. with a minimum pore size of 3.0 µm can be used. Large filter pore size is to prevent excessive pressure drop. The instrument is normally operated at 24 hr. sampling cycle. The supplied vacuum source is an oil-less carbon vane pump of 7.2 cfm free-flow capacity.

Price as of late 1975: $2,200

Supplier: U.S. - Research Appliance Company

Canada - Hoskin Scientific Limited.

Sierra Ambient Cascade Impactor Model 215, 213 and 216:

Use: Aerosol sampling for size distribution and respirable mass in both outdoor and indoor environments

Basic Principle: Inertial Impaction

Particle Size Classification: Yes

Number of Stages: Model 215 - 5, plus 1 backup filter
Model 213 - 3, plus 1 backup filter
Model 216 - 6, plus 1 backup filter

50% Particle Cut-off Size: For spherical particles with special gravity of 1, at 0.75 cfm, 25^{o}C and 760 mm Hg

Stage No.	Diameter	
	Model 215	Model 216
0		16.0 μm
1	9.0 μm	8.6 μm
2	3.9 μm	3.9 μm
3	2.4 μm	2.4 μm
4	1.2 μm	1.2 μm
5	0.61 μm	0.61 μm
Backup filter	0.61 μm >d	0.61 μm > d

Particle Collection: Yes

Flow Rate: 0.5 ft^3/min nominal for all models

Collection Media: Glass fiber filter

Power: 115 Va.c., 60 Hz; 75 Watts (Model 205 and 205 EF vacuum supply)

Dimensions: Model 215: 2.5" (dia) X 4.5" (h)
Model 216: 2.5" (dia) X 6.25" (h)

Weight: Model 215: 2 lbs

Model 216: 3 lbs

Description:

The Model 215 Ambient Cascade Impactor consists of 5 impactor stages and a 47 mm dia glass fiber backup filter. The impactor uses radial slot jets to deposit particles on 47 mm dia., slotted glass fiber filter.

The Model 213 is identical to the Model 215 except that only three impactor stages (No. 1, 2 and 3) are used. A brush-less a.c. pump with flow-meter (called Model 205 vacuum supply) is available from the manufacturer as an option for the above mentioned impactors. The Model 215 S is a complete sampling system including a Model 215 impactor, a Model 205 pump and a piece of 15 feet interconnecting vacuum tubing.

The Model 216 is a 6 stage version of this impactor series. This model is intended for particle classification in the size range between 0.5 µm and 15 µm.

Price as of late 1975: Below $1,400. depending on the construction material and number of stages.

Supplier: U.S. - Sierra Instruments Incorporated

Canada - Applied Research Products Limited.

California Measurements Piezo Particle Microbalance:

Use: Direct monitoring of aerosol mass concentration as a function of particle size

Basic Principle: cascade impaction of particles for piezo-electric determination of mass concentration

Particle Size Classification: Yes, 10 Size Fractions

Particle Size Range: 0.05 µm to 25 µm

Detectable Range: 10 $\mu g/m^3$ to 60,000 $\mu g/m^3$

Particle Collection: Collected particles are not suitable for subsequent analysis.

Description:

The California Measurements Piezo Particle Microbalance (PPM) is a piezo-electric cascade impactor. It uses adhesive-coated quartz crystals as impaction surfaces to capture airborne particles as they emerge from decelerating air jets. The change in frequencies of electronics oscillators controlled by these crystals provides an indication of the mass of the particulates accumulated on each crystal.

The sampling stack of this portable instrument can be detached from the electronics control unit and can be placed in a remote sampling location. Frequency counter and printer are optional accessories for this aerosol microbalance.

This new PPM is capable of measuring particles between 0.05 µm and 25 µm in ten size fractions. It became commercially available since July 1976.

Supplier - California Measurements

(4) Miscellaneous Impactors:
IBC Particle Mass Concentration Meter Model PM40

Use: Automatic measurement of airborne particulate mass concentration

Basic Principle: Inertial impaction of particles onto a quartz crystal micro balance

Particle Size Classification: No

Particle Size Range: 0.3 μm to about 50 μm

Detectable Range: Up to 2,000 $\mu g/m^3$

Particle Collection: Yes

Flow Rate: 0.02 ft^3/min

Output Signal: Direct meter reading in $\mu g/m^3$ with zero to + 2 V d.c. scale recorder output for both mass concentration and accumulated mass.

Power: 115/230 V a.c., 50/60 Hz; 18.5 VA

Weight: 13 lbs.

Description:

The IBC particle Mass Concentration Meter uses aerodynamic impaction mechanism to deposit particles onto an adhesive-coated quartz crystal whose resonant frequency decreases in proportion to the mass. There is another quartz crystal exposed to the same environment as that of the sensing crystal but it receives no impacting particles. The two crystals are parts of two identical oscillators respectively. The frequency of the reference oscillator is around 10^6 Hz and is about 3000 Hz higher than that of the sensing oscillator. These two oscillations are then mixed to obtain beats. Since the beat frequency is proportional to mass of particles deposited onto the sensing cyrstal, changing rate of beats is thus proportional to mass

concentration if the instrument samples air at a fixed flow rate.

With an identical flow circuit the Model PM40 also impacts particles onto a rotating adhesive-coated vitreous graphite disc. Therefore particle analysis is possible with this mass concentration meter.

This portable instrument has wide operating temperature and humidity ranges.

Price as of late 1975: $3,000

Supplier: Hoskin Scientific Limited

Sierra Virtual Impactor Series 240

Use: Particle sampling in respirable and non-respirable fractions

Basic Principle: Inertial separation

Particle Size Classification: Yes (two fractions - larger and smaller than 3.5 μm)

Number of stages: 2

Particle Collection Frequency: See Fig 20

Particle Size Range: Up to 18μm

Particle Collection: Yes

Flow Rate: 0.49 ft^3/min (14 litres/min) total - 0.48 ft^3/min (13.72 liters/min)

Respirable; 0.01 ft^3/min (0.28 liters/min)

Non-respirable

Real-time Readout: No

Collection Media: 37mm membrane or glass fiber filter

Power: 115 V a.c., 50/60Hz; Model 241 - 500 Watts, Model 242- 100 Watts; 24 V d.c. and 230 V a.c. are optional

Dimensions: Control Module = 15" (w) X 18" (d) X 8" (h)

Sampling Module - 30" (dia. of tripod base circle) X 40" (h)

Weight: Control Module - 45 lbs

Sampling Module - 15 lbs

Description:

By impacting large particles (larger than 3.5 μm) into void, the virtual impactor separates airborne particulate matter into two fractions. Both large and small particles are then collected onto 37 mm filters for subsequent analysis.

These instruments have two virtual impactor stages to achieve a good collection efficiency of better than 95% for typical atmospheric particles (see Fig. 21).

The control module of the Model 243 impactor can be located up to 30 feet from the sampling module for convenient sampling. The sampling module which consists of a virtual impactor and a filter holder is mounted on a collapsible tripod. The flow circuits of the instrument include a constant flow controller to eliminate errors caused by filter loading or temperature and pressure changes. The Model 243 comes with a sampling inlet designed for ambient air sampling. For in-line testing or laboratory applications, 243A is identical impactor without the sampling inlet. The control module has a built-in timer/programmer allowing selection of sampling period up to seven days.

Price as of late 1975: Model 243 - $3,895
Model 243A - $3,645
*F.O.B. Carmel Valley, California

Supplier: U.S. - Sierra Instruments, Inc.
Canada - Applied Research Products, Limited

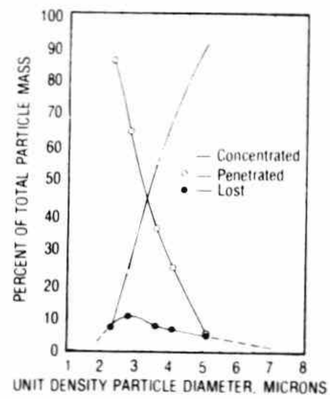


FIGURE 20: Collection Efficiency of Sierra Series 240 Virtual Impactors

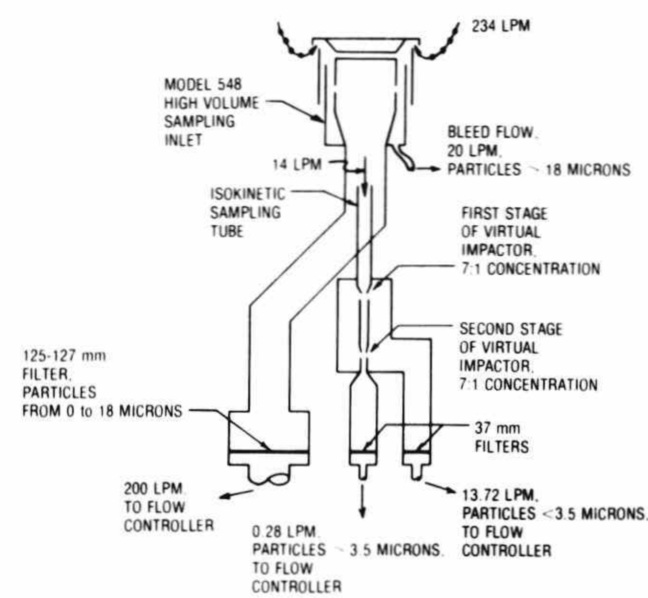


FIGURE 21: Flow Schematic of Sierra Virtual Impactor Model 241

(5) Impingers:

BGI Multistage Liquid Impinger

Description:

The Liquid Impinger has 3 stages for sampling viable organisms between 1 μm and 9 μm in diameter. The instrument has a pyrex body and therefore it can be observed easily while sampling. Three models for different flow rates of 10, 20, and 50 liter/min are available.

Supplier: U.S. - BGI Incorp.

Canada - Hoskin Scientific Ltd.

Greenburg-Smith Impinger

Description:

This impinger is designed for the evaluation of occupational health hazards. The dimensions of this all glass instrument are: 2.25"(dia) X 15"(h).

Supplier: Willson Products Division, ESB Inc.

MSA Midget Impinger

Description:

This impinger is normally operated with a hand pump. Therefore it requires no electric power and can be used for samples containing explosive gases. The impinging liquid can be either alcohol or water. The sampling rate of the impinger is 0.1 ft^3/min. Its dimensions are: 5"(w) X 11.75" (d) X 7.5"(h).

Supplier: Mine Safety Appliance Co.

NEI (Bendix) Midget Impinger

Description:

This glass impinger has a sampling flow rate of 0.1 ft^3/min at a pressure of (2" of water. The jet speed is about 230 ft/sec. With a portable pump the impinger can be used as a personal sampler. Approximate dimensions of the impinger are: 1"(dia) X 7.75: (h).

Supplier: National Environmental Instruments, Inc.

(6) Cyclones:

For ambient air sampling, cyclones are normally available as part of a compact air sampling system which can be easily "worn" by the user and thus often called "personal samplers" (or lapel samplers). Most of these "personal samplers" use filters in series with cyclones to collect respirable particles which escape from cyclones deposition. The following list is to provide brief information about cyclone used in some popular air sampling systems.

BDX Super Sampler and RAC Personal Sampler

Description:

An identical 3-piece cyclone is used by both instrument. The nominal diameter of this cyclone is 1 cm and is intended to collect non-respirable particles of 5 µm and larger at a flow rate of about 0.07 ft^3/min. 37 mm filters is a common collector for respirable particles (smaller than 5 µm) downstream of the cyclone.

Price as of late 1975: BDX sampler - $650 to $750
RAC sampler - $275 to $330

Suppliers: BDX Sampler - U.S. National Environmental Instruments Inc.
Canada - Levitt Safety Eastern Ltd.
RAC Sampler - U.S. Research Appliance Company.
Canada - Hoskin Scientific Ltd.

NEI (Bendix) Respirable Dust Samplers

Description:

The stainless cyclones used in these samplers are available in both 1 inch and 0.5 inch nominal diameter. They are designed to simulate the upper respiratory tracks at a recommended flow rate of about 0.3 ft^3/min. A high efficiency filter is used to collect escaping particles. Supplier: National Environmental Instruments, Inc.

Sierra Fine Particle Sampler and Cyclone Preseparator Model 230 CP

Description:

The Fine Particle Sampler contains an aluminum miniature cyclone with sharp cut-off size to collect particles 2 µm and larger at a flow rate of about 1 ft^3/min. Particles smaller than 2 µm are collected onto a 47 mm filter for analysis. The sampler can be used at a smaller flow rate. When sampling at about 0.3 ft^3/min, the particle cut-off size of the cyclone become 3.5 µm. Parallel to the cyclone-filter combination, the sampler has an additional 47 mm high efficiency filter to collect total suspended particles.

The Cyclone preseparator is an attachment for the standard "Hi-Vol" sampler. This cyclone is intended to exclude re-entrained dust particles. Therefore, the particle cut-off size is about 12 µm at the flow rate of 40 ft^3/min. For other sampling flow rates, the particle cut-off size is proportional to the inverse square root of the flow rate.

This cyclone is made of aluminum and weights 15 lbs.

It has dimensions of 12.25" (w) x 40" (l) x 17" (h) when fully assembled.

Price as of late 1975: Fine Particle Sampler - $2,795
Cyclone Preseparator - $995
*F.O.B. Carmel Valley, California

Supplier: U.S. - Sierra Instruments, Inc.
Canada - Applied Research Products, Ltd.

C. Radiation Aerosol Detectors

(1) Paper Tape Samplers

CAT Model P 101 Particulate Monitor:

Basic Principle: Filtration and radiation extinction

Particle Size Classification: No

Particle Size Range: 0.5 μm and larger

Particle Collection: Yes

Flow Rate: 1 ft^3/min (27 LPM)

Built-in Evaluator: Yes

Direction Indication of Particle Concentration: Yes (in Coh value)

Size of Sample Spot: 1" dia.

Power: 115 V a.c., Gottz

Dimensions: 19"(w) X 8"(d) X 11"(h)

Weight: 25 lbs

Supplier: Canadian Applied Technology, Arrow Flight Holdings Ltd.

Gelman Paper Tape Samplers:

Basic Principle: Filtration

Particle Size Classification: No

Particle Size Range: 0.5 μm and larger

Particle Collection: Yes

Flow Rate: 0.4 ft^3/min (11 LPM)

Built-n Evaluator: No

Collection Media: Type W-41 filter tape

Size of Sample Spot: 0.5"dia

Power: 115 V a.c. 50/60 Hz, 1 amp or

230 V a.c.50/60 Hz, 0.5 amp.

Dimensions: 10"(w) X 10.25"(d) X 10.75"(h)

Weight: 22 lbs.

Supplier: Gelman Instruments Co.

Leigh System Air Particulate Tape Samplers

Basic Principle: Filtration and light extinction

Particle Size Classification: No

Particle Size Range: 0.5 μm and larger

Particle Collection: Yes

Flow Rate: 2.4 ft^3/min (67.5 LPM)

Built-in Evaluator: Model I & II - Yes Model III - No

Direct Indication of Particle Concentration - Model I & II: print-out in optical density units or RUD units

Collection Media: 1.5" wide Whatman #4 tape

Power: 115 V a.c., 60 Hz, 5.5 amps

Dimensions: 20"(w) X 16"(d) X 27"(h)

Weight: 60 lbs

Supplier: Leigh Systems, Inc.

RAC Air Samplers & Monitors Model G Series

Basic Principle: Filtration and light extinction

Particle Size Classification: No

Particle Size Range: 0.5 μm and larger

Particle Collection: Yes

Flow Rate: 1 ft^3/min (27 LPM)

Built-in Evaluator: Model G2 - No; Model G2.R - reflectance evaluator, Model G2.T - transmission evaluator; Model G2.RT reflectance and transmission evaluators; Model G2.SE transmission evaluator

Size of Sample Spot: 1" dia.

Filter Capacity: 100 ft (for 600 samples) or 600 ft (3600 samples)

Power: 110 V a.c., 60 Hz, 2 amps (5.6 amps for the external pump)

Dimensions: 600 ft tape units - 20.75"(w) X 12"(d) X 18.75" (h)

100 ft tape units - 20.75"(w) X 12"(d) X 11.5" (h)

Weight: 600 ft tape units - 55 lbs

100 ft tape units - 47 lbs

external pump - 27 lbs

Price as of late 1975: Range from $1.700 to $2,350

Supplier: U.S. - Research Appliance Co.

Canada - Hoskin Scientific Ltd.

(2) Beta Gauges:

<u>GCA Particulate Monitors</u> - <u>Model APM and RDM Series</u>

Use: Measurement of particle mass concentration.

Basic Principle: Beta ray attenuation by particles, filtration and/or inertial separation.

Particle Size Classification: Yes

Particle Size Range: 0.5 µm to 50 µm

Mass Concentration Range: Model APM - 1 $\mu g/m^3$ to 3×10^5 $\mu g/m^3$
Model RDM.101 - 20 $\mu g/m^3$ to 2.5×10^4 $\mu g/m^3$.
Model RDM.201 - 500 $\mu g/m^3$ and higher.
Model RDM.301 - 10 $\mu g/m^3$ to 3×10^4 $\mu g/m^3$.

Particle Collection: Yes

Flow Rate: Model APM - 0.32 ft^3/min (9LMP)
Model RDM.101 - 0.07 ft^3/min (2LPM)
Model RDM.201 - 0.07 ft^3/min (2LPM)
Model RDM.301 - 0.05 to 0.09 ft^3/min (1.5 to 2.5 LPM)

Collection Media: Model APM and Model RDM.201-glass fiber filter, Model RDM 101 and 301 - plastic film

Power: Model APM - 115 V a.c., 60 Hz; 400 watts
Model RDM 101 and 201 - Ni-Cd rechargeable batteries
Model RDM.301 - 115/220 V a.c., 50/60 Hz or rechargeable batteries.

Dimensions: Model ADM - 20.5" (w) x 14.2(d) x 15.8"(h)
Model RDM.101 - 3.5"(w) x 9.1"(d) x 7.3"(h)
Model RDM 201-3.6"(w) x 9.1"(d) x 7.3"(h)
Model RDM 301-13"(w) x 18"(d) x 10.6"(h)

Weight: Model APM - 22.7 lbs (with pump)
Model RDM - 101 - 1.36 lbs
Model RDM-201 - 1.36 lbs
Model RDM 301 - 6.8 lbs

Description:

All these GCA particulate monitors are beta gauges. The Model APM measures total and respirable particles simultaneously with two sets of filter sampling heads and beta radiation source/detector system particle collection and beta counting take place at the same time. The instrument has digital printouts for aerosol concentration in microgramme per cubic meter of air. The particle sampling period can be preprogrammed for any duration between 1 and 99 minutes. The beta counting time can also be set at a period between 1 and 99 minutes. Ambient air is sampled at a flow rate of 60 cfm at the inlet of the monitor to simulate sampling conditions of a "Hi-Vol" sampler. However, only a small fraction of this primary air sample is extracted isokinetically by the filter at a flow rate of 0.32 cfm. For total particle concentration monitoring, the Model APM has a one size version available. If desired, a standard 0.5" cyclone can be used to separate "non-respirable" particles from "respirable".

The RDM (Respirable Dust Monitor) series are all portable instruments. The Model 101 utilizes a two-stage particle collection system to sample air at a small flow rate of 2 LPM (see Fig. 22). The first stage of the instrument is a cyclone precollector for the retention of "non-respirable" particles. The collection efficiency of the cyclone drops from very high for particles larger than 10 μm to very low for particles smaller than 2 μm in diameter. Particles escaping collection from the first stage are deposited onto a thin plastic film by a circular nozzle impactor for beta attenuation measurement. The instrument provides direct reading of particle

mass concentration in milligrams per cubic meter of air.

The Model RDM.201 is similar to 101 except that a 1.4 cm dia. fiber glass filter is used in Model 201 to collect "respirable" particles (see Fig. 23).

The Model RDM 301 has a two-stage particle collection system also. It accepts two types of pre-collectors, the 10mm nylon cyclone and the MRE horizontal elutriator. The second collection stage of this model is a circular nozzle impactor. A plastic film disc is used to provide 450 collection spots for small particle impaction. The instrument produces direct digital print out of the mass concentration for a selected period as well as the total accumulate mass. All of these particulate monitors use any half life Carbon-14 for beta radiation source.

Price as of late 1975: Model APM - $9,950
Model RDM.101 - $3,500
Model RDM.201 - $3,700
Model RDM.301 - $7,700
*U.S. price, F.O.B. Bedford, Massachusettes

Supplier: GCA/Technology Division.

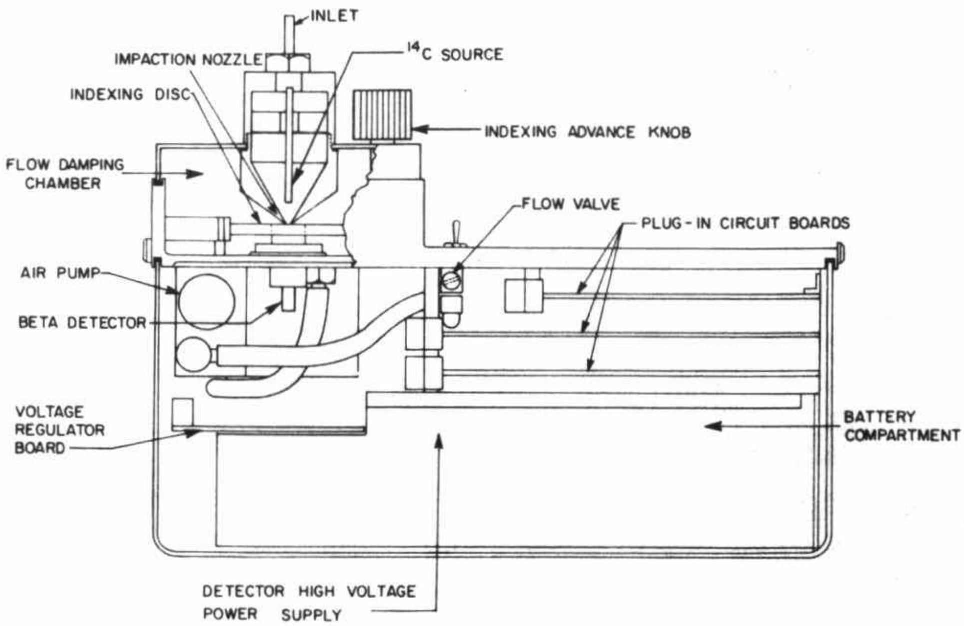


FIGURE 22: Internal View of the GCA Respirable Dust Monitor Model RDm-101

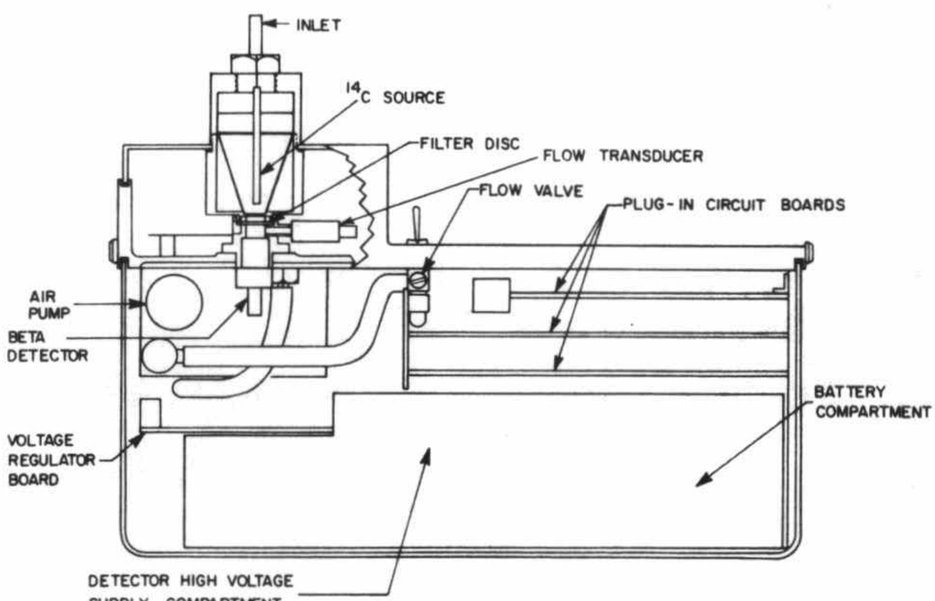


FIGURE 23: Internal View of the GCA Respirable Dust Monitor Model RDM-201.

LSI Monitors Models PM/ARGOS I and II

Use: Measurements of mass concentration of industrial emissions and ambient air

Basic principle: Filtration and beta ray attenuation

Particle Size Classification: No

Particle Size Range: 0.5µm and larger

Detectable Range: Particle concentration higher than that of ambient air

Particle Collection: Yes

Description:

The PM/ARGOS I is an automated instrument for continuous measurement of stack particulate emissions. The PM/ARGOS II is designed for monitoring particulates in both ambient air and occupational environmemt. Both instruments utilize filter tapes to collect particles for mass concentration using beta radiation absorption technique. The control unit of these devices is separated from the sampling unit for convenient operation

Supplier: Lear Siegler Inc.

Philips Dust Monitor PW 9790

Use: Continuous monitoring of particle mass concentrations in air

Basic Principle: Filtration and beta ray absorption

Particle Size Classification: Possible with an optional particle separator

Particle Size Range: Dependent on the type of air inlet in use

Particle Concentration Range: $5 \mu g/m^3$ to 1.08×10^6 $\mu g/m^3$

Particle Collection: Yes

Flow Rate: 0.6 ft^3/min (1 m^3/hr) to 1.8 ft^3/min (3^{m^3}/hr)

Output Signals: Digital output plus 0 to 10V electric signal for recorder

Collection Media: Glass fiber filter tape

Size of Sample Spot: 2 cm^2

Power: 110/127/200/220/245 V a.c.50/60 Hz

measuring unit: 35 watts; control unit: 25 watts
pump" 250 watts

Dimensions:	Measuring unit:	23"(w) X 14.7" (d) X 342.5" (h)
	or	58.5 cm (w) X 37.3 cm (d) X 870 cm (h)
	Control unit:	14.9"(w) X 9.6"(d) X 16.5" (h)
	or	37.8 cm (w) X 24.4 cm(d) X 41.8 cm (h)
	Pump:	15.8" (w) X 6.3" (d) X 14.2" (h)
Weight:	Measuring unit:	21.4 lbs (47 kg)
	Control unit:	7.5 lbs (16.5 kg)
	Pump:	7.3 lbs (16 kg)

Description:

The standard dust monitor PW 9790 consists of a measuring unit, a control unit and a vacuum pump. The measuring unit contains a filter tape drive system, a heated air sampling gate and a beta source/detector system. The control unit has all electronics used for a up-down counter and D.C. power supplies.

As illustrated in Fig. 24, beta radiation from a low-level source is passed through the clean glass fiber filter and is measured with a Geiger counter. The output of the Geiger counter is pulse signal. The number of pulses are counted with the up-down counter over a preset counting period in the range between 10 seconds and 4 minutes. After sampled air is drawn through the filter, the same section of the filter is exposed to the beta radiation again. Since the dust particles collected on the filter absorb beta radiation, the count-rate is reduced accordingly. By counting down from the pulse number attained with the clean filter toward zero, a new counting period longer than the preset period is obtained. The difference in time between the up and down counting periods is directly related to the mass of particle collected on the filter. Using artificial aerosols, the instrument is calibrated to express the result in micro-gramme per cubic meter of air.

There is an air intake attachment (PW 9737) and a particle separator (PW-9738) available from the manufacturer as options for the instrument to restrict the size of suspended particles allowed into the measuring unit of the monitor.

Price as of late 1976: Dust monitor (PW 9790) - $11,000
Air Intake Attachment (PW 9737) - $650
Particle Separator (PW 9738) - $493

Supplier: Philips Electronics Industries, Ltd.

User's Comment:

"...the Philips Dust Monitor...appears to have a direct dimensional correlation with the "High Volume" Sampler within specified accuracy limits."

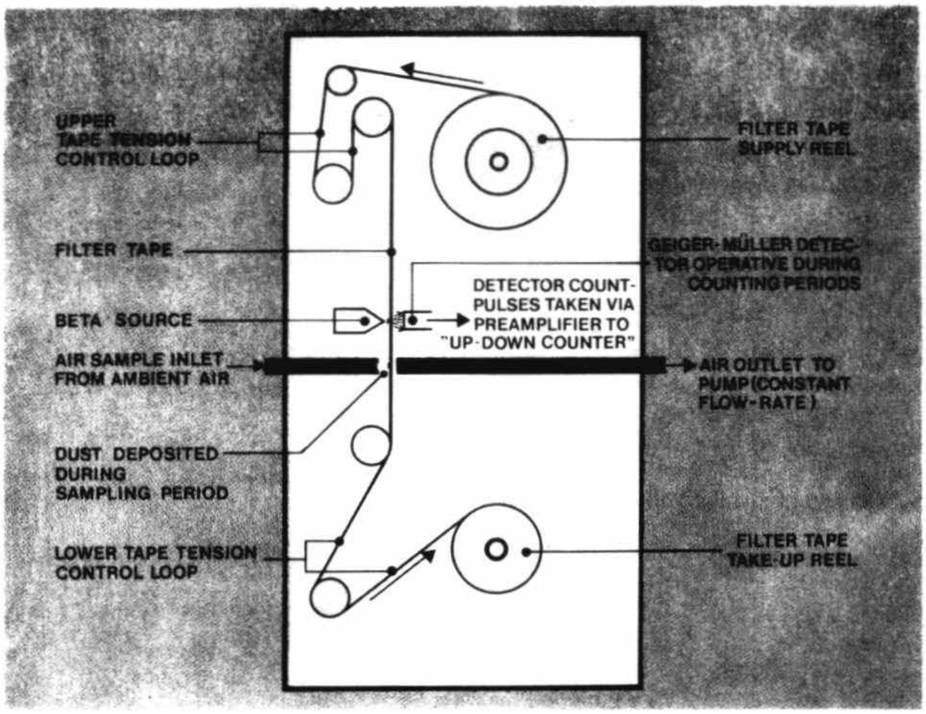


FIGURE 24: Physical Arrangement of Philips Dust Monitor PW 9790

(3) Aerosol Photometers and Optical Particle Counters

ATI Particulate Detection Apparatus TDA-2D and 727 Particulate Detector

Use: Ambient and occupational air monitoring for suspended particles

Basic Principles: Forward light scattering photometry

Particle Size Classification: No

Particle Size Range: 0.3 μm to 10 μm

Particle Collection: No

Flow Rate: 1 ft^3/min (30 LPM)

Output Signal: % penetration of light indicated on a meter

Power: 100 to 130 Va.c. 47 to 63 Hz.

Description:

The TDA-2D Particulate Detection Apparatus is a portable forward scattering photometer. This new instrument replaces the Model TDA-2C which is originally designed for filter testing. The new version is also intended for dust measurement in occupational environments.

The optical arrangement of TDA-2D is illustrated in Fig. 25. Before operation, the instrument is balanced electronically with clean air in the scattering chamber. The span calibration can be carried out by using the internal calibration circuit which is set for 100 ug of 0.3 μm particles or using any other chosen aerosols to simulate actual sampling conditions. The standard instrument is equipped with a linear scale meter for percentage penetration of light. A four place digital readout is optional.

The Model 727 Particulate Detector is a similar photometer without some of the automatic functions of the Model TDA-2D. The Model 727 also uses forward scattering technique to achieve some detection sensitivity of the Model TDA.2D. The 727 is designed particularly for clean room testing and for constant

monitoring of filter banks.

Price as of late 1975: Model TDA.2D - $2,600

Model 727 - $1,100

Supplier: U.S. - Air Techniques Inc.

Canada - 0 D.M.E. Ltd.

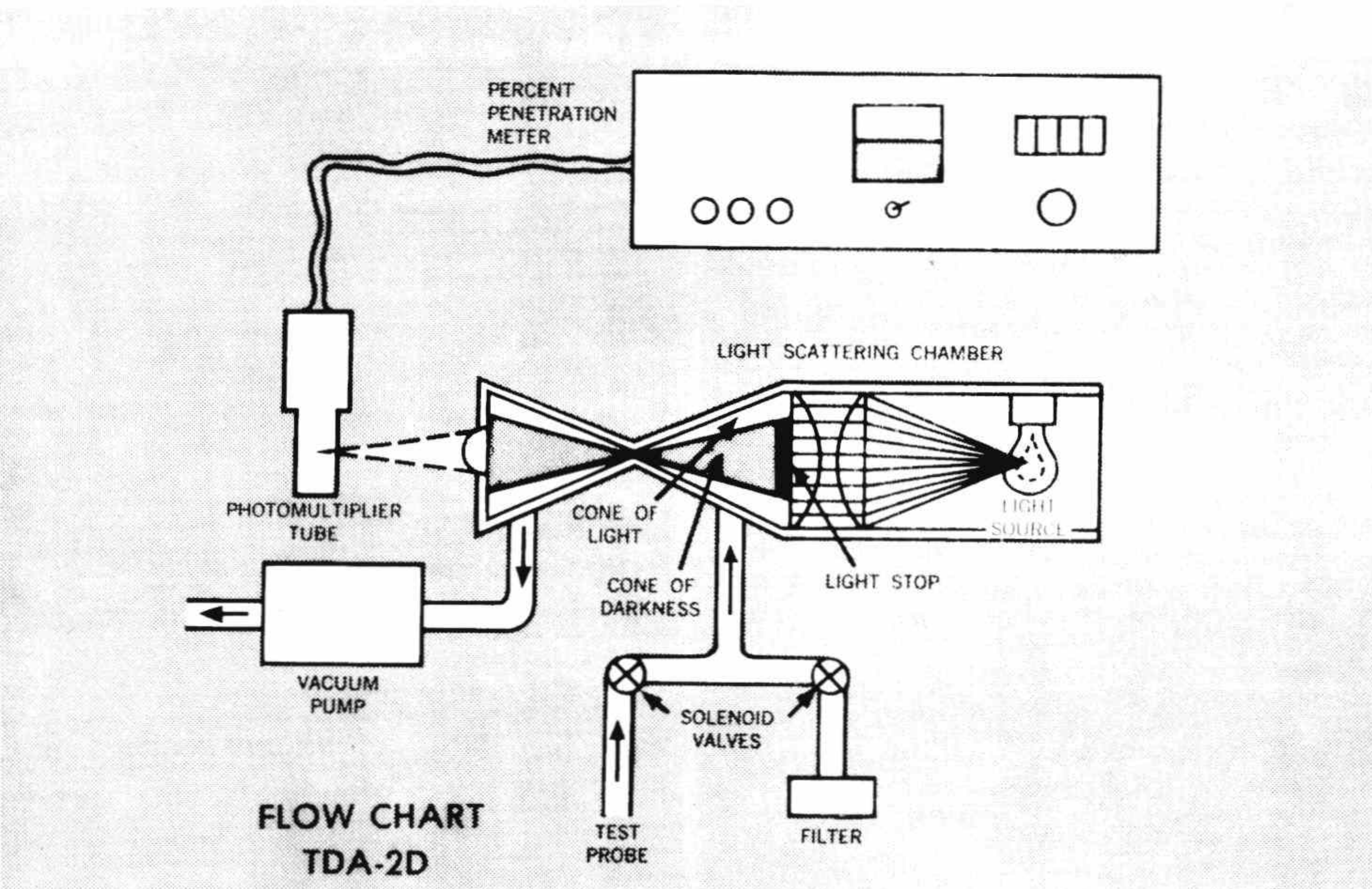


FIGURE 25: Flow Chart of ATI Particulate Detection Apparatus TDA-2D

Bausch & Lomb Aerosol Particle Counter 40-1A

Uses: Ambient air and clean room monitoring.

Basic Principles: Near-forward light scattering photometry.

Particle Size Classification: Yes, in 7 size increments.

Particle Size Range: 0.3 µm to 10 µm

Particle Concentration Range: 0 to 10^6 particles/ft^3

Particle Collection: No

Flow Rate: 0.17 liter/min

Output Signal and Display: Analog logarithmic panel meter for direct readings in particles/m^3 of air plus a rare panel accessory jack for the optional Digital Readout or Printer.

Power: 115 V a.c./ 60 Hz; 220 Vac/50 Hz - available on special order.

Dimensions: 11"(w) x 11"(d) x 18"(h) or 28 x 28 x 46 cm

Description:

The Bausch and Lomb 40-1A Aerosol Particle Counter uses the near-forward light scattering principle utilizing a mean acceptance angle of 40^o. Air, to be sampled, is drawn through a small view volume (about 0.5 mm^3) which is illuminated by a tungsten light source. A concentric optical system collects the light scattered by the individual particles at the view volume. Pulses, generated in a photodetector in response to the collected radiation, are amplified and detected in a pulse-amplitude discriminator. The sensitivity of the amplifier is adjusted by the particle-size switch and the discriminator passes only those pulses greater than the predetermined size. A pulse rate that is related to particle passage rate is then fed to an electrical

current meter which is calibrated to give direct readings of particle concentrations per cubic foot or liter of air.

The 40-1 A counts all particles above the present size of 0.3, 0.5, 1.0, 2.0, 5.0 and 10.0 μm. Calibration of the instrument is done at the factory using transparent polystyrene latex spheres of known size.

Price as of October 1976*: $3,595

Supplier: U.S. - Bausch & Lomb

Canada - Bausch & Lomb Canada

* F.O.B., Rochester, New York.

<u>Climet CI.201 Particle Analyzer</u> and <u>CI.208 Airborne Particle Counter</u>

Uses: Air Quality measurement, industrial process and clean room monitoring

Basic Principles: Wide angle forward light scattering (see Fig. 26)

Particle Size Classification: Yes, CI.201 - 6 size ranges
CI.208 - 5 size ranges

Particle Size Range: CI.201 - 0.3 μm and larger
CI.208 - 0.5 μm and larger

Particle Concentration Range: 0 to 10^7 particles/ft^3 of air

Particle Collection: No

Flow Rate: 0.25 ft^3/min

Output Signal and Display: CI.201 - (1) Analog logarithmic panel meter for concentration readout in particle/m^3
(2) 0 to 1V recorder output proportioned to particle concentration
CI.208 - 5 place digital display

Power: 115 V a.c., 60 Hz; 250 watts

Dimensions: CI.201 - 19"(w) X 24"(d) X 7.5"(h)
CI.208 - 20"(w) X 22"(d) X 8"(h)

Weight: CI.201 - 72 lbs
CI.208 - 60 lbs

Description:

The CI-201 is the basic sensor of the Climet particle analysis system. The optical arrangements of this sensor measures light scattered by individual particles in forward direction covering a 60° solid angle (see Fig. 26). The view volume of this instrument is 2.2×10^{-8} cubic feet and is positioned at the primary focal point of an elliptical mirror. A photomultiplier tube is situated

at the secondary focal point of the ellipse to detect particle scattering which is reflected and collimated by the mirror.

The sampled air drawn into the view volume is sheathed by a laminated tube of clean air to prevent particles from being trapped and recirculated in the sensor chamber. The result of counting is displayed with a panel meter in six selectable size ranges (0.3 µm, 0.5 µm, 1 µm, 5 µm and 10 µm). If counting and recording of particle concentration as function of size is desired, a programmable recorder (CI-209) is available from the manufacturer for continuous monitoring.

The Model CI-208 is similar to CI-201 in design. This instrument is intended for continuous long-term measurement of airborne particles in an industrial environment. The CI-208 has a five place digital readout for particle counting in five size ranges equal to and greater than 0.5; 1; 3; 5 and 10 µm.

Supplier: Climet Instruments Company

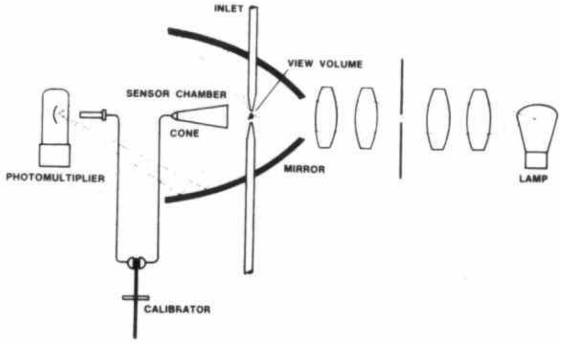


FIGURE 26: Optical System of Climet CI-201 Particle Analyzer

Dynac M-201B Automatic Particle Monitor

Use: Monitoring particulate concentration in controlled environment

Basic Principle: Light scattering detection

Particle Size Range: 0.5 µm to 5 µm

Detectable Range: Up to 10^6 particles/ ft^3

Particle Collection: No

Flow Rate: 0.1 ft^3/min

Output Signal: Manual 6 digit display counter in particles/ft^3 with options of automatic timed printing counter and digital strip chart.

Power: 105 to 125 V a.c., 60 Hz.

Dimensions: 17"(w) X 12(d) X 7" (h)

Weight: 30 lbs.

Description:

The M-201B is an aircraft carry-on permitted portable photometer. The instrument is designed for use in monitoring airborne particulate matter in clean rooms and other area of controlled environment. The monitor is equipped with an audible alarm for filter leak detection. The threshold particle sizes for monitoring are 0.5, 1.0, 3.0 and 5.0 µm.

Supplier: Dynac

ESC Pills IV and Pills V

Use: Measurement of particle concentration in stack, process stream or other occupational environment

Basic Principle: Pills IV - infra-red near forward scattering
Pills V - infra-red back scattering

Particle Size Classification: Pills IV - yes; Pills V - no

Particle Size Range: Pills IV - 0.2 µm to 50 µm
Pills V - 0.05 to 10 µm

Detectable Range: Pills V - 0.005 grains/ft^3 to 20 grains/ft^3

Particle Collection: No

Sampling Volume: 0.73 cubic inches (or 12 cm^3)

Display: Panel meter

Power: 115 V a.c., 60 Hz

Description:

Both Pills V and Pills IV are infra-red photometers using laser as a radiation source. Pills V is designed for measurement of particle concentration in stacks and process streams. This instrument detects light scattered backward from an unperturbed sampling volume located several inches away from the end of a probe. By utilizing an infra-red radiation source (wave length is 0.9 µm) detected signal is practically proportional to the scatting volume of all measurable particles.

The Pills IV is for on-line measurement of particle size distribution and particle concentration in occupational environment. The instrument detects radiation scattered by a single particle at two different angles in near forward direction. The ratio of two measured scattering intensities allow the instrument to give an accurate estimate of the particle size.

Price as of late 1975: Pills IV - $24,600

Pills V - $ 6,400

Supplier: U.S. - Environmental System Corp.

Canada - Aimark Ltd.

MRI Integrating Nephelometer Model 1550, 1560 and 1561

Uses: Measurement of atmospheric visual distance and its related quantity of airborne particulate concentration

Basic Principle: Detection of scattered light over a very wide angle from a tube of air sample

Particle Size Classification: No

Particle Size Range: 0.1 μm to 10 μm

Detectable Ranges:

Model	1550	1560	1561
Scattering coefficient ($10^{-4}m^{-1}$) -	0.1 to 100	0 to 40	0 to 10
Visual distance (mile) -	100 to 0.3	10 to 0.65	50 to 2.5
Mass Concentration (ug/m^3) -	0 to 3800	0 to 1520	0 to 380

Particle Collection: No

Flow Rate: 5 ft^3/min - all models

Output Signal: Panel meter with 0 to 5 V d.c. output at external terminals

Power: 105 to 125 V a.c., 60 Hz; Model 1550 - 1 amp, 70 watts max. Model 1560 and 1561 - 60 watts max.

Dimensions: Model 1550 - electronic and power supply
19"(w) x 11"(d) x 7"(h)
Optical assembly
4" (dia) x 44" (l)
Model 1560 and 1561 - 13"(w) x 8"(dia) x 41"(h)
or 33 cm(w) x 20.3 cm(d) x 104.1 cm(h)

Weight: Model 1550 - 52 lbs total
Model 1560 and 1561 - 38 lbs.

Description:

The Integrating Nephelometer was developed originally for

the meteorological measurement of visual range. The Model 1550 consists of a tubular optical assembly, an air pump and an electronics unit. The air sample is continuously drawn through the cylindrical optical chamber at a fairly fast flow rate of 5 c.f.m. (see Fig. 27). The long, tubular air sample is then illuminated with white light from a pulsed xenon lamp attached to the center of the chamber. A photo-multiplier located at one end of the optical chamber receives direct and reflected particle scattering covering angles from 8° to 170° (see Fig. 13).

CO_2 and Freon-12 are standard gases for the calibration of the instrument. An accessory air heater (Model 416) is recommended by the manufacturer to eliminate moisture effects when the relative humidity of air is above 70%. The instrument has been used successfully for airborne measurements.

The Model 1560 and 1561 are photon counting nephelometers different from each other only in sensitivity (Model 1560 covers a particle concentration range 4 times higher than of Model 1561). The instrument is assembled in one environmentally protected unit. A continuously operating quartz-halogen incandescent lamp covered with an opal glass is used to illuminate the particles. With an additional photo-tube to monitor the light source, a constant illumination of air sample is maintained by means of an electronic regulator.

Price as of late 1975: Model 1550 - $5,842 Canadian; $5,585 U.S.
Model 1560 and 1561 - $4,153 Canadian, $3,970 U.S.
*F.O.B. Altadena, California

Supplier: U.S. Meteorology Research Inc.

Canada - Carleton Instruments Ltd.

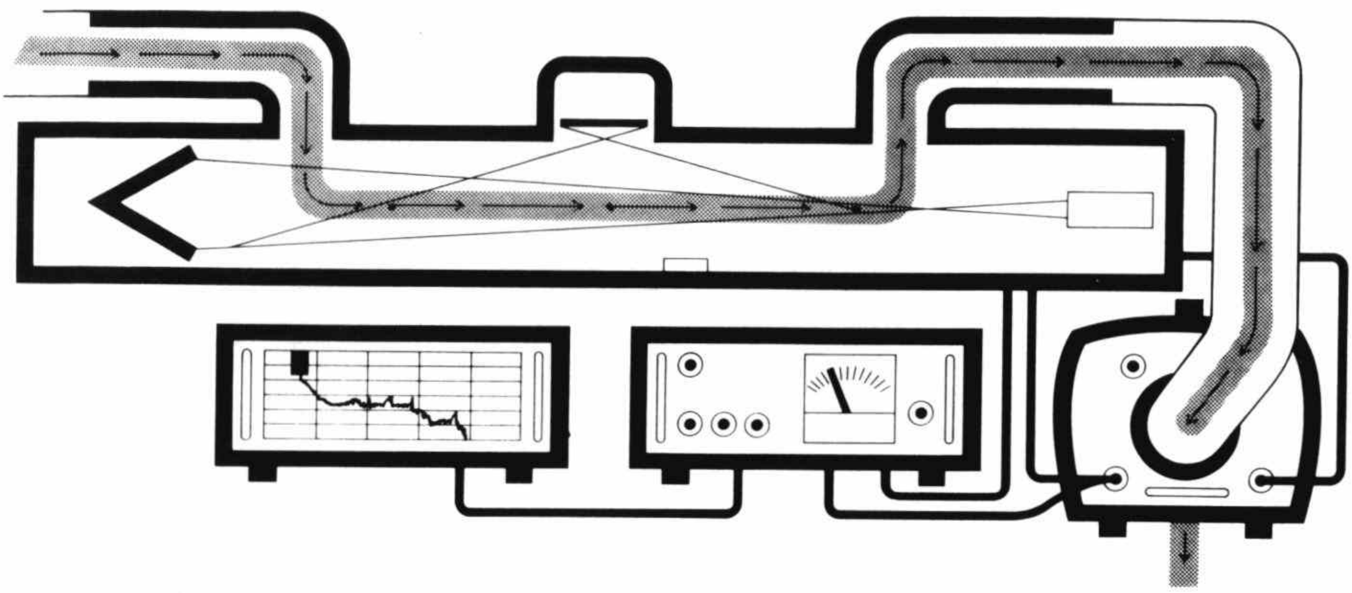


FIGURE 27: MRI Integrating Nephelometer Model 1550

Royco Particle Counters Model 203, 218, 220, 225, 240 and 245

Uses: Monitoring airborne particle concentration and/or size distribution in clean room or ambient air

Basic Principle: Scattered light detection in near forward or 90^{o} direction

Particle Size Classification: Yes (with incremental selection) except Model 203 and 240

Particle Size Range: 0.3 μm and larger or 0.5 μm and larger

Detectable Range: Model 203, 220 - 0 to 10^6 particles/ft^3

Model 218 - 0 to 10^7 particles/ft^3

Model 225 - 0 to 10^8 particle/ft^3

Model 240 - 0 to 10^4 particle/ft^3

Model 245 - 0 to 10^5 particle/ft^3

Particle Collection: No

Flow Rate: Model 203 and 218 - 0.01 ft^3/min

Model 220 - 0.1 ft^3/min

Model 225 - 0.1 or 0.01 ft^3/min

Model 240 and 245 - 1ft^3/min

Output Signal: Choice of digital display, analog or d.s. output for strip chart recorder

Power: 115/230 V a.c. at 50/60 Hz

Model 203 and 220 - 150 watts

Model 218 - a.c./d.c. operated

Model 225 and 245 - 225 watts

Model 240 - 30 watts

Dimensions: Model 203 - sensor unit: 16.55"(w) X 18.5"(d) X 10.5"(h)

readout unit: 16.75"(w) X 21"(d) X 8.5"(h)

Model 218 - 15.5"(w) X 10.5"(d) X 4"(h)

Model 220 - 16.75"(w) X 18.5"(d) X 10.5" (h)

Model 225 and 245 - main frame: 16.75"(w) X 21"(d) X 8.5"(h)

sensor: 5.25"(w) X 21"(d) X 4"(h)

Model 240 - sensor: 5.25"(w) X 21"(d) X 4"(h)

flow control unit: 16.75"(w) X 10.5"(d) X 5.25"(h)

power supply unit: 16.75"(w) X 10.5"(d) X 5.25"(h)

Weight: Model 203 - sensor unit = 32 lbs.

readout unit = 38 lbs.

Model 218 - 23 lbs.

Model 220 - 32 lbs.

Model 225 and 245 - main frame = 49 lbs.

sensor = 12 lbs.

Model 240 - sensor = 12 lbs.

flow control unit = 20 lbs.

power supply unit = 18 lbs.

Description and Comments:

The series of Royco Particle Counters are designed to monitor particle concentration according to their sizes by measuring scattered radiation at either right angle or near forward direction. The viewing volume of these instruments is very small (about 2 cubic millimeters) and the sampled air is also diluted to avoid having more than one particle viewed at a time.

The Model 203 is intended for counting particles 0.3 µm and larger at a relatively small sampling rate of 0.01 cfm. The instrument counts total number of particles without size

discrimination. The 90° scattering technique is used for optics of Model 203.

The Model 218 is a portable light scattering photometer which can be operated on regular a.c. power or a rechargeable battery. The sample durations can be set at either 1 or 10 minutes. The minimum particle size is selectable at 0.5, 1, 2, 3, 5 and 10 μm. The instrument indicates measured results with a six digit readout display.

The Model 220 measures scattered light from the particle at a 90° angle. This model counts particles in two ranges (larger than 0.5 μm or larger than 5 μm) simultaneously. The flow rate is 0.1 cfm. If desired, additional particle ranges can be provided on special order.

The Model 225 is for automatic sizing of airborne particles up to the concentration of 10^8 particles per cubic foot of air. The flow rate of this model is selectable (either 0.1 or 0.01 cfm). The optical arrangement of the Model 225 is near forward light scattering measurement. The minimum detectable particle size is 0.5 μm.

The Model 240 consists of 3 separate units: a flow controller, a power supply and a particle sensor. The sensor is small and can be located remotely for convenient measurement. The instrument is designed specially for clean room monitoring up to a concentration of 3×10^4 particles per cubic foot of air. The Model 240 counts all particles 0.5 μm in diameter or larger at 1 cfm flow rate. An additional size range of 5 μm and larger is available as an option.

The Model 245 and Model 225 are similar aerosol photometers. However, 245 has a fixed high flow rate of 1 cfm and a low maximum detectable concentration of 10^5 particles per cubic foot.

There is a plug-in module #508 for both Models 245 and 225 to count particles automatically in 5 continuous adjustable size ranges. While the Model 225 is intended for atmospheric particle measurement, the Model 245 is more suitable for clean room and laboratory analysis.

All Royco Particle Counters are factory calibrated with standard polystyrene latex particles. Any important deviation in optical properties of particlesmay cause significant error in estimated particle size.

Price as of late 1975:* Model 218 - $3,085

Model 220 = $10,000

Model 225 = $7,040

Model 245 = $6,345

* F.O.B. Toronto.

Supplier: U.S. - Royco Instruments Inc.

Canada - Ralph E. Benner Ltd.

Sartorius Aerosol Photometer S

Uses: Continuous filter testing, clean room supervision, emission control and atmospheric monitoring for particulate matter

Basic Principle: 45^{o} light scattering photometry

Particle Size Classification: No

Particle Size Range: Down to size of gas molecule

Detectable Range: 10^{8} particle/cm^{3} to 5 X 10^{2} particles/cm^{3}

Particle Collection: No

Output Signal: Digital read out and recorder signal to indicate particle mass concentration

Power: 220 V a.c.

Description:

The photometer S is a new version of the Model Sm. The light source of this instrument is a low voltage standard lamp. A photo-multiplier measures radiation at a 45^{o} scattering angle. The light detector also monitors the intensity of the radiation source interruptedly to permit automatic compensation for changes in particle illumination. The instrument measures particle concentration in every 10 seconds.

Supplier: Germany - Sartorius - Membranfilter GmbH
Canada - BDH Chemicals Canada Limited.

Sinclair-Phoenix Aerosol, Dust and Smoke Photometer Model JM 2000 and JM 4000

Uses: Clean room and ambient air sampling for particulate matter

Basic Principle: Near forward scattering photometry and filtration

Particle Size Classification: No

Particle Size Range: 0.05 μm to 40 μm

Particle Collection: Yes

Collection Media: 47mm molecular filter

Flow Rate: 1 ft^3/min

Output Signal: Model JM 2000 - logarithmic amplifier with indicating meter

Model JM 4000 - linear or logarithmic meter with 0 to 25 mV d.c. signal for recorder

Power: Model JM 2000 - 115 V a.c., 60 Hz; 500 watts

Model JM 4000 - 115/200/230 V a.c., 50/60 Hz or 12 V d.c. automotive power kit

Dimensions: Model JM 2000 - 21"(w) X 12"(d) X 16"(h)

Weight: Model JM 2000 - 70 lbs

Model JM 4000 - 36 lbs

Description:

Both models of Sinclair-Phoenix aerosol instruments are similar in principle. Air sample is drawn into the optical chamber continuously at 1 c.f.m. The optical arrangement (see Fig. 28) of the instrument is so designed that when particles enter the small illuminated spot of the chamber, the detector is able to receive all scattered light with scattering angles between 4^o and 36^o. If microscopic examination or chemical analysis is desired, the detected particles can be

collected efficiently onto a molecular filter downstream of the optical sensor.

The Model JM 4000 is an improved version of JM 2000. The new model is more portable and can be equipped with a pistol grip probe. The sensitivity of the Model JM 4000 is also higher than the original model. The manufacturer recommends Freon - 12 for filter testing and instrument calibration.

Price as of July 1975: Model MJ 2000 - $2,900

Model MJ 4000 - $3,495

Supplier: Phoenix Precision Instrument

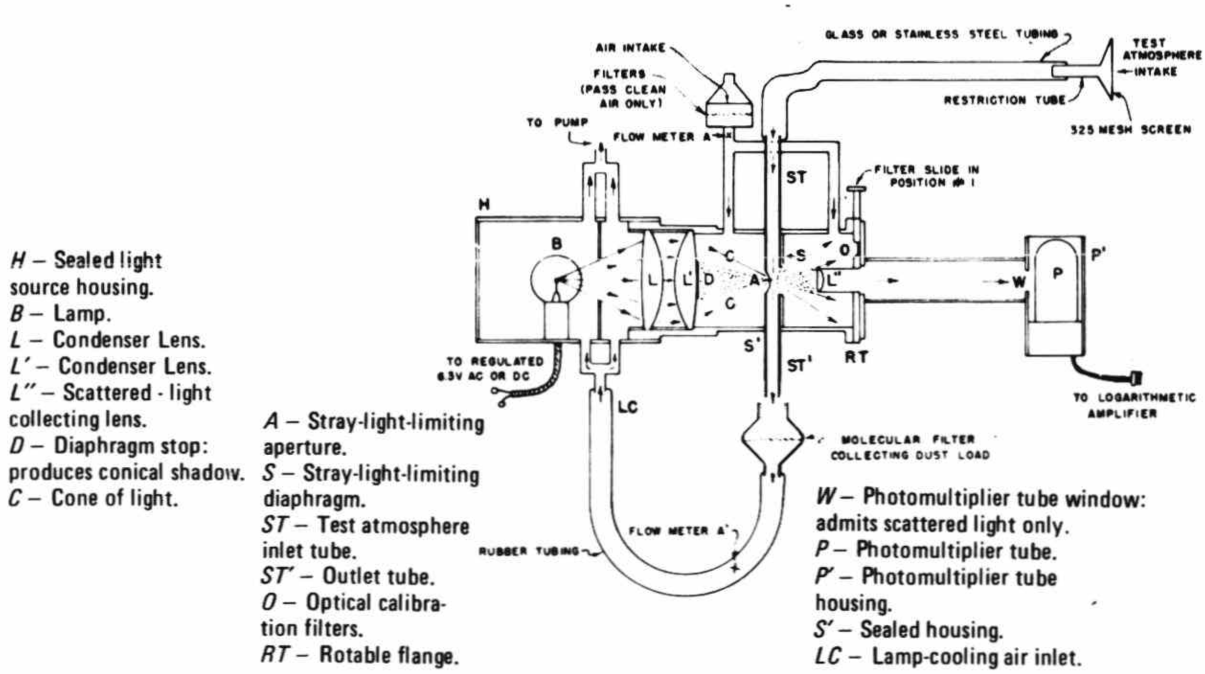


FIGURE 28: Sinclair-Phoenix Aerosol Monitoring System

<u>WM Model AP-3 Digital Dust Indicator</u>

Use: Industrial dust survey

Basic Principle: Right angle scattered light detection

Particle Size Classification: No

Particle Size Range: 0.3 µm to 5 µm

Detectable Range: 10 $\mu g/m^3$ to 5 X 10^5 $\mu g/m^3$ (average mineral dust)

Particle Collection: No

Flow Rate: 0.35 ft^3/min (10 liters/min)

Output Signal: Panel Meter to indicate concentration in count/min; also 4-digit mechanical register

Power: 9 "c" batteries (1.5 V each)

Dimensions: 10.75"(w) X 3.25"(d) X 6.75"(h)

Weight: 7.25 lbs

Description:

The AP-3 Dust Indicator aspirates air sample into the instrument with an internal fan. Dust particles in a illuminated air volume scatter light at a 90^0 angle to the incident beam onto a photo-multiplier tube. When a given amount of radiation is detected, a capacitor is discharged into the electronic circuitry as a pulse. These electrical pulses are displayed on a rate meter with a capacity up to 10,000 counts per minute.

This portable light photo meter is designed as a relative indicator of dustiness for field use. The manufacturer also supplies a formula to convert counting rate to particle mass concentration in milligram per cubic meter.

Supplier: U.S. - Weather Measure Corp.

Canada - Analygas Systems Limited

(4) Condensation Nuclei Counters

BGI Model P Condensation Nuclei Counter

Uses: Cloud and aerosol studies; filter efficiency test

Basic Principle: Condensation of water vapor upon sub-micron particles to obscure radiation

Particle Size Classification: No

Particle Size Range: 0.005 μm to 1 μm

Detectable Range: 10 particles/cm^3 to 5 X 10^5 particles/cm^3

Particle Collection: No

Output Signal: 0 to 10 μA ammeter

Power: 6V, 100 amp-hr. storage battery

Weight: 50 lbs

Description:

The model P consists of a long optical tube wetted ceramic lining on inner wall to provide necessary moisture for particle condensation. A photodetector is located at the bottom measuring transmitted radiation from the light source at the top of the optical tube. A hand pump is used to draw air sample into the instrument. After air sample is pressurized with clean air, it is allowed to be saturated with water vapor. The mixture is then expanded adiabatically to decrease the temperature very quickly. At the created low temperature, water vapor condenses on nuclei and the droplets grow to the same final diameter regardless of initial particle size. The measured reduction in stransmitted light intensity, which corresponds to the concentration of nuclei, is converted into electrical signal by the instrument and displayed.

Price as of late 1975: $7,000

Supplier: U.S. - BGI Inc.

Canada - Hoskin Scientific Ltd.

Environment/One Model Rich 100 Condensation Nuclei Monitors and Photographic Submicron Particle Counter

Uses: Real-time measurement of the concentration of submicron airborne particles for air quality monitoring, meteorology and is effluent detection and clean room supervision.

Basic Principle: Measurement of light attenuation by droplets created from water vapor condensation on submicron particles

Particle Size Classification: No (but possible with an attachment called "Diffusion Dennder")

Particle Size Range: 0.0025 μm and larger (0.0016 μm and larger is available on special order)

Detectable Range:	Standard version -	300 particles/cm^3 to 10^7 particles/cm^3
	Portable version -	900 particles/cm^3 to 10^6 particles/cm^3
	Portable/photographic	30 particles/cm^3 to 3×10^4 particles/cm^3

Particle Collection: No

Flow Rate: Standard version - 30 cm^3/sec to 70 cm^3/sec adjustable

Output Signal: Particle concentration indicated in a visual panel meter and recorder output at the range of 1 to 7 v. d.c. For the portable/photograhic Model, photographic recording is possible.

Power: All standard versions - 115 V a.c., 50/60 Hz: 80 watts

Portable version - mercury batteries at 3 V d.c. or 12 V d.c.

Portable/photographic - 115 V a.c., 60 Hz, or rechargable batteries

Dimensions: All standard versions - 14"(w) X 13"(d) X 8"(h)

Portable version - 10'(w) X 6"(d) X 12"(h)

Portable/photographic - 7"(w) X 9"(d) X 5"(h)

Weight: All standard versions - 39 lbs

Portable version - 8 lbs

Portable/photographic - 7 lbs

Description:

These instruments operate on the theory that water vapor condenses on submicron particles to produce visible droplets when supersaturated. In operation, air sample is pumped into the cloud chamber of the instrument through a humidifier. A quick fixed volume expansion of the sample produces a water cloud whose density is directly proportioned to the concentration of "Aitken" nuclei in the sample. As the light intensity of the optical system is attenuated by the cloud, an electrical pulse is generated and amplified to produce a d.c. signal proportional to the nuclei concentration. There are Special features such as automatic range changer, low particle count capability and response to 0.0016 μm particles available for all standard versions.

The portable nuclei counter is a compact version intended for field use. The portable/photographic Model is specially designed for "absolute" concentration measurement of submicron particles by means of recording the cloud on self-processing photographic film.

Price as of late 1975: Model Rich 100

Standard Unit: $4,570.

With automatic range changer: $5,950.

Low particle count version: $5,050

With small particle response: %,670

Portable Model - $1,450

Portable/Photographic - $1,150

Supplier: Environment/One Corp.

Gardner Small-Particle Detector Type CN

Uses: Studies of industrial emissions, automobile exhausts and meteorological effects of submicron particles

Basic Principle: Condensation of water vapor upon submicroscopic particles for light detection

Particle Size Classification: Size discrimination of the instrument is adjustable

Particle Size Range: 0.001 um and larger

Detectable Range: 2×10^2 nuclei/cm^3 to 1×10^7 nuclei/cm^3

Particle Collection: No

Output Signal: Panel meter to indicate particle number per cubic centimeter

Power: Battery operated

Dimensions: 5.13"(w) x 7.88"(d) x 18"(h)

Weight: 10 lbs

Description:

This small nuclei counter contains a long cloud chamber which has a lamp at the top and a light detector at the bottom. The cloud chamber is saturated with water vapor by a moist blotter and is connected to an auxiliary chamber through a quick opening valve. A hand pump is used to draw air sample into the cloud chamber as well as to provide the vacuum for the expansion and to purge the instrument.

After sample is drawn into the counter, the auxiliary chamber is disconnected from the cloud chamber and evacuated. Since the air is saturated with water vapour in the cloud chamber when the quick-opening valve is opened the sudden expansion causes a substantial temperature drop thus resulting information of visible droplets if condensation nuclei are present. The

light transmitted through the cloud chamber to reach the photocell is reduced according to the total number of droplets produced. A calibrated micro ammeter is used to measure the photocell current and to indicate the concentration of Aitken nuclei in number of particles per cubic centimeter of air.

Price as of late 1975: $522. *F.O.B. Schenectady, N.Y.

Supplier: Gardner Associates, Inc.

(5) Laser Holography

Laser Holography Inc. Particle Analysis System and Imanco Hologram Analysis System

Use: Detailed examination of airborne particles in situ for the size, shape and velocity

Basic Principle: Reconstruction of particle image from hologram which contains coherent light interferrence pattern of the particle

Particle Size Information: Yes

Particle Size Range: 0.3 µm to 1,000 µm

Detectable Range: About 10 particles per frame

Particle Collection: No (But particle image can be recorded for repeated examinations)

Output Signal: Particle images on TV screen and/or recorder

Dimensions: Laser - 8"(w) x 50" (d) x 8"(h)
Camera - 4"(dia) x 26"(l)
Minimum length of the set-up - 80"
Image reconstructor - 30"(w) x 96"(d) x 31"(h)

Weight: Laser - 40 lbs
Camera- 10 lbs
Image Reconstructor - 600 lbs

Description:

The Particle Analysis System uses a ruby rod laser to illuminate a small air volume containing particles. The formed hologram is recorded by a camera. After the picture is developed, a magnified image of particles is then reconstructed and displayed on a TV screen. Since the laser is very rapidly pulsed, fast moving particles with speed up to about 3,000 meter per second can be "captured".

By forming particle image directly on the vidicon within the camera, an instantaneous monitoring of aerosols is also possible. Particularly designed for size distribution and the growth of droplets in aerosol spray, the real-time holographic system produces particle images for motion picture effect. The video images can be stored at the same time for later viewing in slow motion. With an image analysis computer, particle size distribution can be obtained very quickly.

Price as of late 1975*: Laser system - $30,000
Image processing system - $60,000
Image analysing mini computer - $20,000
*The actual cost which can vary over a wide range is available from manufacturer upon request.

Supplier: Holographic system - Laser Holography Inc.
Image analysing system - Imanco

D. Aerosol Precipitators

Del Model ESP - 100 A Air Particle Sampler

Use: Collection of airborne particles in a wide size range for various applications

Basic Principles: Electrostatic precipitation

Particle Size Classification: No (but two stages sampling is possible with the attachment of a cyclone or elutriator)

Particle Size Range: 0.025 μm and larger

Particle Collection: Yes

Flow Rate: 27 ft^3/min

Power: 100 V/ 115 V/ 200 V/ 220 V a.c., 50/60 Hz

Dimensions: Sampling head - 4"(dia) X 20"(l)

Power supply - 6"(w) X 4.75"(d) X 3.25"(h)

Weight: 16 lbs

Description:

The ESP-100 A is an improved version of the Model ESP-100. This portable electrostatic precipitator is constructed in two separable assemblies - a high voltage power unit which can be carried with a shoulder strap and a sampling unit which can be hand-held. The sampling unit contains an air blower, a flowmeter, the high voltage electrodes and a sampling tube 1.75 inches in diameter by 12 inches long. These two units can be either clamped together for fixed position sampling or inter-connected with a 5 feet flexible power cable for breathing zone sampling.

The instrument maintains a very high corona current along a stainless steel wire located axially at the air inlet end of the sampling head to generate positive ions (see Fig. 29). Particles in sampled air are charged quickly by these ions and attracted toward the negatively charged collection tube. By

splitting the flow stream into two annuli, both inner and outer sides of the tube are useful for particle collection. Therefore, the length of the precipitation zone of the instrument is very efficiently shortened.

This precipitator utilizes positive corona to reduce the generation of ozone, by a by-product of high voltage discharge which is often undesirable for aerosol sampling.

Price as of January 1976- $795

Supplier: Del Electronics Corp.

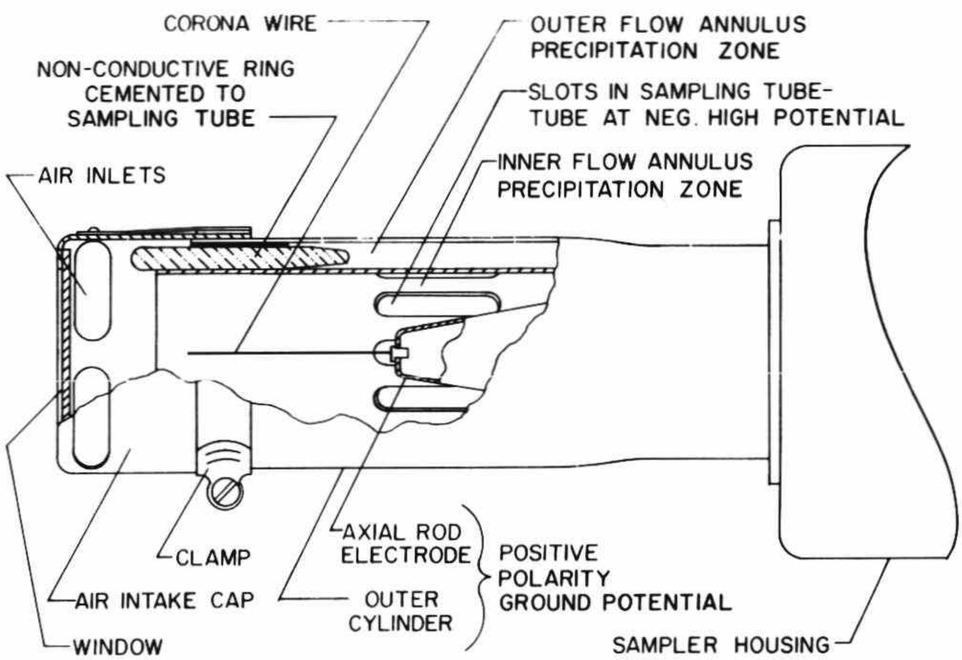


FIGURE 29: Cut-Away Diagram of Del Model ESP-100A Sampling Head

Sci-Med Large Volume Air Sampler Model LVS.2K and KVS/10K

Uses: Hospital surveillance, clean room monitoring and measurement of particle concentration in ambient air

Basic Principle: Electrostatic precipitation and inertial impaction

Particle Size Classification: No

Particle Size Range: 0.3 µm and larger

Particle Collection: Yes

Flow Rate: Model LVS/2K - up to 70 ft^3/min (2,000 liters/min)
Model LVS/10K - 70 ft^3/min to 353 ft^3/min, adjustable (2,000 liters/min to 10,000 liters/min)

Collection Media: Water or other suitable liquid

Power: 110 V a.c., 60 Hz

Dimensions: Model LVS/2K - 19"(w) X 18.25"(d) X 14"(h)
Model LVS/10K - 25.88"(w) X 25.25"(d) X 19"(h)

Weight: Model LVS/2K - 55 lbs
Model LVS/10K - 95 lbs

Description:

The LVS samplers were initially designed for the collection of biological aerosol particles. The two models differ from each other only in their flow rate. The instrument has a collection chamber sitting on a power cabinet. An air inlet with a calibrated nozzle is located at the top of the sampler. After the air sample is drawn into the collection chamber, it is forced to flow radially outward between two horizontal plates. Airborne particles are negatively charged by the corona discharge of a ring of needles attached vertically to the high voltage plate at the top. Since the bottom plate is at positive ground potential, it attracts particles

and collects them on its surface.

The precipitated particles are then concentrated in a liquid flowing over the collection plate and finally gathered in a fluid reservioir. Soft water is the recommended collection liquid for this instrument.

Price as of late 1975: LVS/2K - $5,000
LVS/10K - $6,000

Supplier: Sci-Med Inc.

TSI 3100 Electrostatic Aerosol Sampler 3200 - Series

Particle Mass Monitor Systems and Model 3500 Respirable Aerosol Mass Monitor:

Use: Aerosol mass monitoring for various applications

Basic Principle: 3100 - electrostatic precipitation

3200 - electrostatic precipitation and piezoelectric mass detection

3500 - impaction and electrostatic precipitation

Particle Size Classification: 3100 and 3200 - no

3500 - only respirable particles (0.01 um $< d <$ 3.5 um) are measured

Particle Size Range: 3100 - 0.02 µm to 10 µm

3200 - 0.01 µm to 10 µm

3500 - 0.01 µm to 3.5 µm

Detectable Range: 3100 - up to 5,000 $\mu g/m^3$

3200 - 2 $\mu g/m^3$ to 2,000 $\mu g/m^3$

3500 - 10 $\mu g/m^3$ to 10,000 $\mu g/m^3$

Particle Collection: No

Flow Rate: 3100 - 0.14 ft^3/min to 0.35 ft^3/min (4 litres/min to 10 litres/min)

3200 - 0.04 ft^3/min (1 liter/min)

3500 - 0.04 ft^3/min (1 liter/min)

Output Signal: 3100 - 5 digit sampling cycle counter

3200 - strip-chart recording of concentration plus 0-5 V d.c. analog output

3500 - 4 digits display in mg/m^3 or Hz

Power: 3100 - 115V a.c., 60 Hz; less than 250 watts

3200 - 115V a.c., 60 Hz; 200 watts

3500 - a.c./d.c. operated; built-in rechargable Ni-Cd batteries

Dimensions: 3100 - 15"(w) X 9"(d) X 7"(h) or
38 cm(w) X 23 cm(d) X 18 cm(h)
3200 - 17.3"(w) X 12.2"(d) X 7.1"(h) or
44 cm(w) X 31 cm(d) X 18 cm(h)
3500 - 12.2"(w) X 5.1"(d) X 6.7"(h)
31 cm(w) X 13 cm(d) X 17cm (h)

Description:

The 3100 Electrostatic Aerosol Sampler is an automatic portable instrument for general airborne particle collections. The sampler precipitates particles between 0.02 μm directly onto optical slides or electron microscope grids.

The particle charging section of this instrument is separated from the particle collection section. In the charging section, particles in the air sample are subjected to alternating pulses of ions from positive corona discharge of a fine wire. The positively charged particles then flow through the collection section. A positive voltage applied to the upper plate of the collection section drives the particles to the lower plate. After all charged particles are deposited, the voltage on the upper plate is shut off automatically and a sampling cycle is completed.

The periodical precipitation of this instrument is to produce a uniform, representative sample. The instrument can also be operated using a constant D.C. precipitation voltage when classification due to particle characteristics is not important.

Series 3200 aerosol instruments consists of a electrostatic precipitator and a quartz crystal microbalance. The

systemincludes a mass monitor module, a vacuum pump and either a digital indicator or a strip chart recorder.

The aerosol to be sampled is drawn through a nozzle, which has a high voltage needle at the center, into the electrostatic precipitator chamber at 1 L.P.M. (see Fig. 30). The particles are then deposited by electric field onto the surface of a piezoelectric quartz crystal oscillating at its resonant frequency. The resonant frequency of the quartz crystal decreases linearly with the total mass of the particulate deposition, thereby detecting the weight of sampled particles. To compensate for possible changes in ambient conditions, the air flow passes a second quartz crystal downstream.

The 3205A and 3210A systems are intended for air quality monitoring because the mass monitor module conditons the entering aerosol for increased particle adhesion to the crystal surface. The former displays the result only in frequency and is for sampling in an environment with rapidly changing conditions. The latter automatically calculates and records particle concentration for long term monitoring.

The Model 3500 respirable aerosol Mass Monitor is a portable electrostatic precipitator measuring only respirable fraction of airborne particulate matter. The particle laden air is drawn into the instrument from the bottom of the monitor. After impacting large particles (3.5 µm and larger) on the impaction surface, sampled air flows horizontally into the precipitators. Particles then flow downward along a high voltage needle and through a nozzle where high intensity negative corona discharge takes place. A quartz crystal at a

small distance below the needle tip is an electrode for the corona discharge and also for particle collection.

The crystal sensor should be cleaned by detergent and water after 5 μg accumulation. A two minute air drying period is required before beginning the next measuring cycle.

Supplier: U.S. - Thermo-Systems Inc.
Canada - Willer Engineering Ltd.

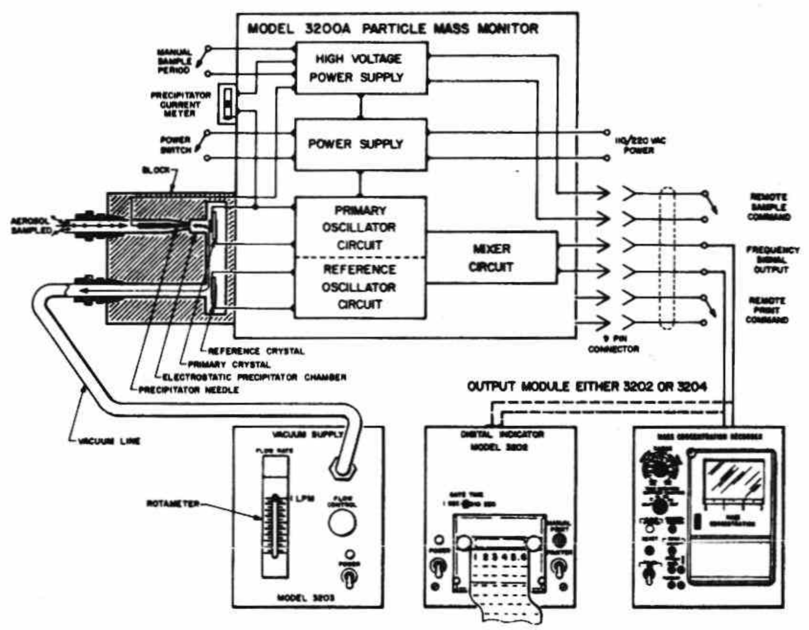


FIGURE 30: TSI 3200-Series Particle Mass Monitor System

Casella Thermal Precipitator

Use: Fine airborne particle collection for detailed studies

Basic Principle: Thermal precipitation

Particle Size Classification: No

Particle Size Range: 100% collection efficiency for particle between 0.01 μm and 5 μm

Particle Collection: Yes

Flow Rate: 2.5×10^{-4} ft^3/min (7cm^3/min)

Power: 12 amp. hr battery (included); 1.3 amps

Dimensions: 7.25"(w) X 7.25"(d) X 14.5"(h) in case

Weight: 17.25 lbs

Description:

This thermal precipitator has two main assemblies: a power unit and a sampling head. The sampling head is made from two metal blocks separated by thin strips of insulating material to form a vertical slot. An electrical resitance wire heated from the power unit passes horizontally across the slot. A pair of water cooled microscope cover glases, 0.75" in diameter, are held vertically on each side of the wire. The distance between the hot wire and the surface of the cool glass is very small. Therefore, all particles in sampled air, which flows downward between the glass plates, are repelled and deposited on the cover glasses.

This instrument is a portable precipitator with the intent that it can be easily operated in a confined space.

Price as of late 1975: $729

Supplier: Europe - C.F. Casella & Co. Ltd.
U.S. - BGI Incorporate
Canada - Carleton Institute Limited

E. Miscellaneous Aerosol Analyzers

Casella Gravimetric Dust Sampler - Type 113A and Hexhlet

Use: Industrial dust assessment

Basic Principle: Gravitational settlement and filtration

Particle Size Classification: Yes (two fractions - respirable and non respirable)

Particle Size Range: Non-respirable - 3.5 µm and larger
Respirable - 3.5 µm and smaller (dependend on filter in use)

Detectable Range: High particle concentration e.g. industrial environment

Particle Collection: Yes

Flow Rate: Type 113A - 0.09 ft^3/min (2.5 liters/min)
Hexhlet - 1.77 ft^3/min (50 liters/min)

Collection Media: Filter

Power: Type 113A - 900 milli amp. hr. rechargable nickel-cadmium battery; 65 milli-amp
Hexhlet - compressed air or 110/120 V a.c., 60 Hz, if the use of a pump is preferred

Dimensions: Type 113A - 9"(w) X 4.5"(d) X 7" (h)
Hexhlet - 20"(w) X 6.5"(d) X 6.5"(h)

Weight: Type 113A - 9.25 lbs
Hexhlet - 11.25 lbs

Description:

The Dust Sampler Type 113A is designed for the assessment of the health hazard of industrial dust, particularly that in mines and foundries. The instrument can collect enough respirable particles for gravimetric weighing in a reasonable time period.

A diaphragm pump driven by a D.C. motor draws air into the sampler at a constant slow flow rate of 2.5 L.P.M. The dust laden air passes a horizontal elutriator followed by a filter disc. The elutriator of the Type 113A is made from flat plates appropriately separated to give long horizontal channels such that non-respirable particles (3.5 µm and larger) settle to the plates before reaching the filter.

There are two interchangeable elutriators available for the sample. The four channel elutriator is designed to have its 50% cut-off size at 5 µm for unit density spheres. This elutriator collects all particles 7 µm in diameter or larger. The eight channel elutriator provides 50% collection of particles which have falling speed equal to that of a 3.5 µm unit density sphere and removes all particles larger than 5 µm in size.

Respirable particles in the sampled air are collected on a 5.5 µm diameter filter of either membrane or glass fibre paper. With a time switch, this portable dust sampler can collect airborne particle unattendedly for a sampling period of up to twelve hours.

The Hexhlet is similar to the Dust Sampler Type 113A in principle. However, the Hexhlet does not require electric power and has a higher sampling flow rate of 50 L.P.M.

The elutriator of Hexhlet is an open ended box containing a large number of thin aluminum plates slotted horizontally into side walls. The elutriator is designed to settle particles 7 µm or larger before the sampled air reaches the end of collection plates. The air sample is normally drawn into the instrument by passing compressed air through an air ejector.

An oil-less or diaphragm pump providing a pressure difference of 215 mm Hg can be used as the air mover if so desired.

The flow rate of Hexhlet is controlled by a critical orifice and a vacuum guage downstream of the elutriator. The orifice is open to a Soxhlet Thimbler filter surrounded by an evacuation chamber. The respirable fraction of particles in sampled air are collected onto the thimbler for subsequent evaluations. For low concentration dust sampling, a 4.25 cm filter disc, either paper or glass fiber is recommended to replace the Soxhlet for more accurate results.

Price as of late 1975: Hexhlet - $816

Supplier: Europe: C.F. Casella & Co. Inc.
Canada: Carleton Instruments Ltd.

Fleming Aerosol Spectrometer Type 501 and 502

Use: Sampling of solid and/or liquid airborne particles in industrial area for particle size distribution.

Basic Principle: Gravitational settlement

Particle Size Classification: Yes

Particle Size Range: 1 μm to 20 μm

Particle Collection: Yes

Flow Rate: Choice of 1.77 X 10^{-5} ft^3/min, 3.53 X 10^{-5} ft/min or
7.06 X 10^{-5} ft^3/min
(0.5 cm^3/min, 1 cm^3/min or 2 cm^3/min)

Collection Media: Glass Slides

Power: Rechargeable battery (included)

Dimensions: 23"(w) X 5.5"(d) X 9"(h)

Weight: 20 lbs.

Description:

The Aerosol Spectrometer Type 501 is an instrument for sampling aerosols in high concentration areas. Using gravitational settling speedof airborne particles, this apparatus classifies and deposits dusts on a row of glass slides.

The air sample is drawn into the horizontal settlement duct of the instrument at a small flow rate selectable among 0.5, 1 and 2 cubic meter per minute. All particles in sampled air are then carried along the duct by clean "winnowing" air and fall at their individual gravitational settling speed. The winnowing air is circulated in a closed system by a diaphragm pump at a constant operation indicating the relationship between particle settling speed and the distance along the collection surface. The instrument can be preset for a sampling period

of 5½, 11 or 22 hours using sampling flow rate of 2, 1, or ½ cm^3/min respectively.

For operation in extremely rugged environment, Type 502 is an instrument similar to Type 501 but equipped with a strong, protective case and very safe electrical circuitry.

Supplier: Fleming Instruments Ltd.

TSI 3030 Electrical Aerosol Size Analyzer and 3071 Electrostatic Classifier

Uses: 3030 - Counting and sizing of airborne particles for various applications

3071 - generating monodispersed particulate matter and analyzing aerosol mobility

Basic Principle: Classification of particles using their electrical mobilities

Particle Size Classification: Yes

Particle Size Range: 3030 - 0.0032 μm to 1 μm

3071 - 0.01 μm to 0.3 μm

Detectable Range: 3030 - 1 $\mu g/m^3$ to 1,000 $\mu g/m^3$

3071 - 10 $\mu g/m^3$ to 1,000 $\mu g/m^3$

Particle Collection for Subsequent evaluation: No

Flow Rate: 3030 - 0.14 ft^3/min (4 liters/min)

3071 - 0.07 ft^3/min (2 liters/min)

Output: 3030 - 3½ place digital readout and 0 to 10 V d.c. electrical signal for recorder

3071 - monodispersed aerosol particles of selectable size

Power: 3030 or 3071 - 115/230 V a.c., 50/60 Hz; 30 watts

Dimensions: 30303 - control circuit/readout unit:

7.9"(w) X 11.8"(d) X 3.5"(h) or

20 cm(w) X 30 cm(d) X 9 cm (h)

flow module:

7.9"(w) X 13.8"(d) X 24.4"(h)

20cm (w) X 35 cm(d) X 62cm (h)

3071 - 7.9"(w) X 13.8"(d) X 24.4"(h)

20 cm(w) X 35 cm(d) X 62 cm(h)

Weight: 3030 - control circuit/readout unit: 8.8 lbs(4 kg)
flow module: 44 lbs (20 kg)
3071 - 44 lbs (20 kg)

Description:

The 3030 Aerosol Size Analyzer measures electrical mobility of airborne particles and is an improved version of the discontinued "Whitby Aerosol Analyzer". The instrument consists of two separate assemblies: a flow module and a control unit. The flow module contains a particle charging section at the top and a particle analyzing section at the bottom (see Fig. 31). When air is pumped into the flow module, positive corona discharge from a high voltage wire within the charge section charges all particles positively. A metal rod, to which a variable negative high voltage can be applied, is located axially through the center of the analyzing section. As the charged particles flow concentrically from the charging section to the analyzing section, they are attracted to the rod. Since all particles have their initial downward speed, only those smaller than a certain size (with high enough electrical mobility) are drawn to the surface of rod when a voltage corresponding to that size is applied. Particles larger than the cut-off size pass through the main analyzing section and are collected downstream by a particle and electrical current collecting filter. Because all particles are electrically charged, the concentration of filtered aerosols is proportional to the electrical current measured by an electrometer connected to the filter.

A step increase in rod voltage results in a decrease in electrometer current. This current decrease is directly

related to the concentration of particles between two discrete sizes. The instrument provides eleven voltage steps to measure ten equal geometrical size intervals covering particle sizes from 0.0032 μm to 1 μm.

The 3030 analyzer can be operated either manually or automatically. It can also be intermittently triggered by an external pulse from a timer for aerosol monitoring over a long period of time.

The 3071 Electrostatic Classifier is an instrument designed to descriminate all sizes of pre-existing airborne particles except those within a chosen narrow size range. To achieve this function, polydispersed aerosols are filtered, dried, then passed through a Kr-85 bipolar charger (see Fig. 32). The charger establishes a bipolar equilibrium charge level on the particles, before they flow into the mobility analyzing chamber.

The differential mobility analyzer of the instrument is a vertical cylinder with a negatively charged metal rod extended axially from the ceiling of the cylindrical chamber. After the charged particles enter the analyzer from its top, their moving path inside the chamber is determined by their individual electrical charge and mass. Since most of the particles with diameters between 0.01 μm and 0.3 μm obtain only unit electrical charge (either polarity), the electrical mobility of a small particle is higher than that of a large particle. Therefore, the small exit at the bottom of the analyzer receives only particles within a narrow size range which are directed toward the exit by the electrical field.

User's Comments on 3030 Electrical Erosol Size Analyzer:

"The bottom channels (smallest sizes) are clearly inoperative,... The larger channels are also of questionable quality, especially for atmospheric monitoring... However, ... the instrument is the only thing I know of which has any science behind it at all."

"The sensitivity of the instrument increase by about three orders of magnitude as the particle diameter varies from 0.0075 µm to 0.75 µm... We have difficulty getting meaningful readings from the first two channels of the Electrical Size Analyzer and I am not so sure of the instrument's performance at the largest size channel...."

"One common application problem of the Model 3030 is the possibility of the sample changing over the measurement cycle of about 2¼ minutes .... In summary, though the Model 3030 must be used with caution in its application, and though one should expect breakdowns, the data provided by it can be very useful when gathered and interpreted by an aerosol scientist...."

Price as of late 1975: 3030 - $11,900 Pump - $500
3071 - $9,880

Supplier: U.S. - Thermo Systems Inc.
Canada - Willer Engineering Ltd.

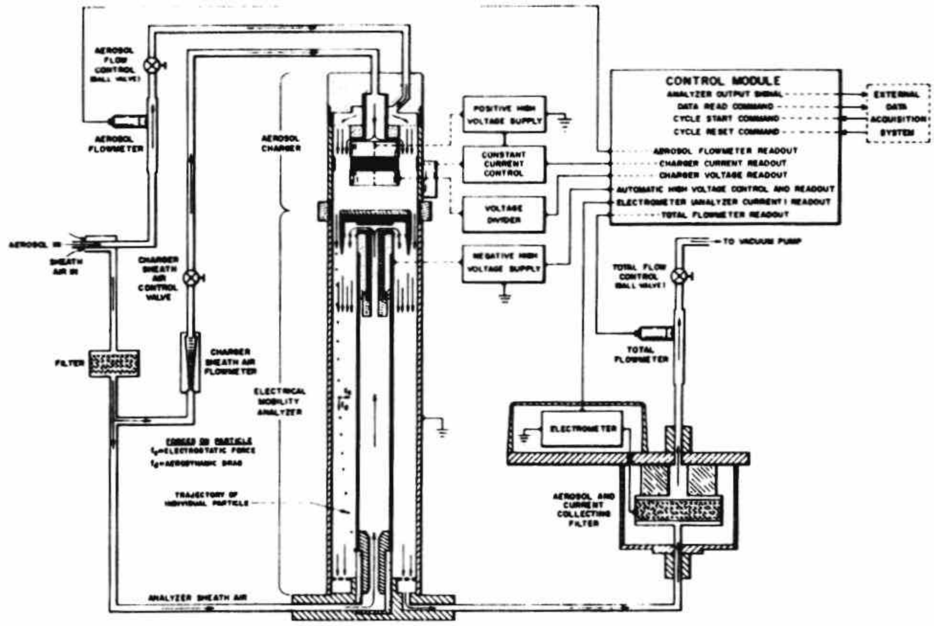


FIGURE 31: TSI 3030 Electrical Aerosol Size Analyzer

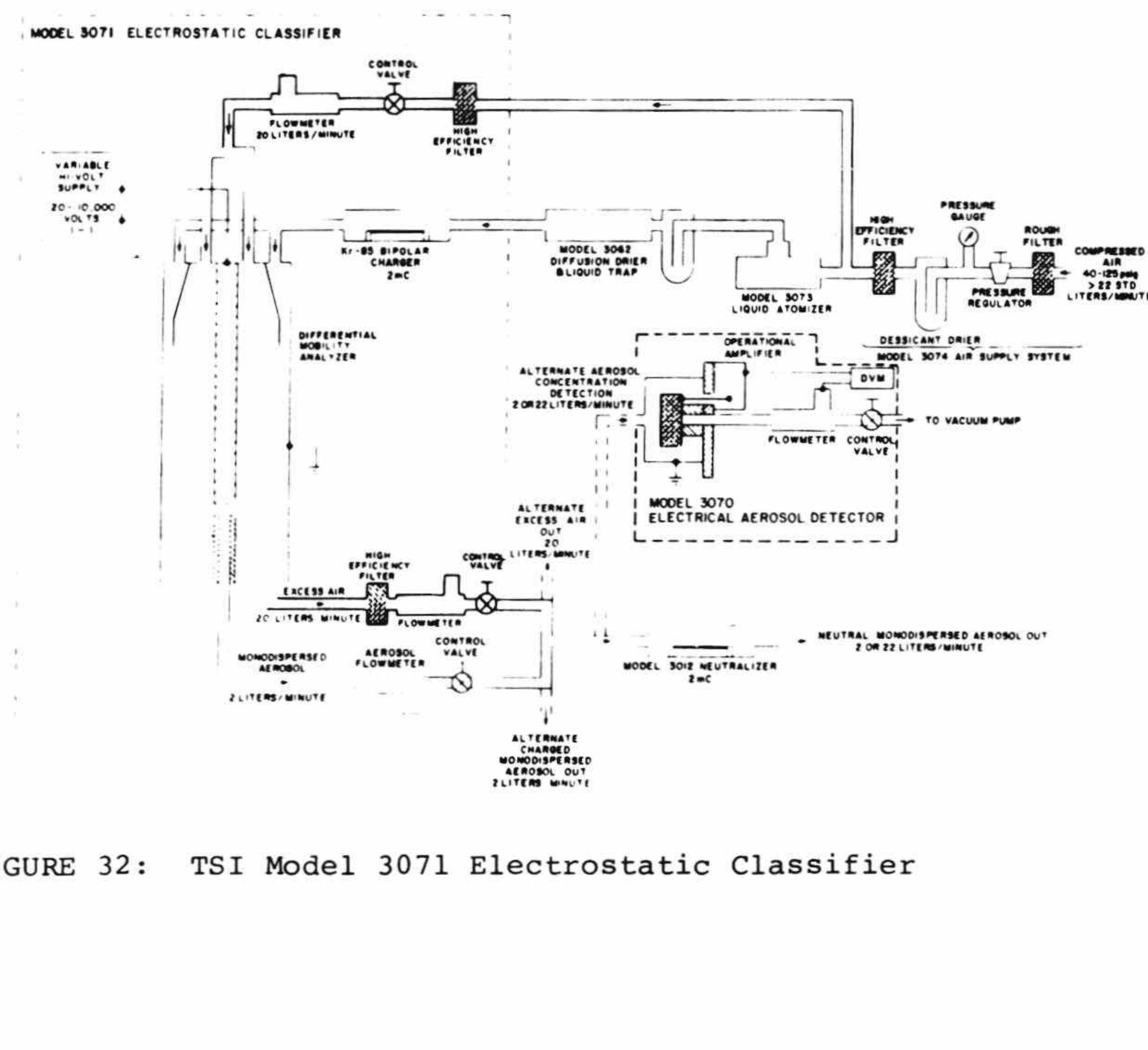


FIGURE 32: TSI Model 3071 Electrostatic Classifier

VIII. APPENDIX

Selected List of Aerosol Instrument

Manufacturers and Distributors

Airmark Ltd.

P.O. Box 756, Streetsville, Mississauga, Ontario, L5M 2C2,
Canada, Tel. (416) 826-3345

Air Techniques Inc.

1717 Whitehead Rd. Baltimore, Maryland 21207, U.S.A.
Tel. (301) 944-6037

Analygas Systems, Ltd.

2220 Midland Avenue, Scarborough, Ontario, M1P 3E6, Canada
Tel. (416) 291-1616

Andersen 2000 Inc.

P.O. Box 20769, Atlanta, Georgia 30320, U.S.A.
Tel. (404) 768-1300

Applied Research Products Ltd.

P.O. Box 624, Station St. Laurent, Montreal, Quebec H4L 4V9,
Canada, Tel. (514) 747-3244

Bausch & Lomb, Analytical Systems Division,

820 Linden Avenue, Rochester, New York 14625, U.S.A.
Tel. (716) 385-1000

Bausch & Lomb Canada, Analytical Systems Division,

2605 Paulus Street, Montreal, Quebec, H4S 1E9, Canada
Tel. (514) 336-1633

BDH Chemical Canada Ltd.

350 Evans Avenue, Toronto, Ontario M8Z 1K5, Canada
Tel. (416) 255-8521

BGI Inc.

1254 Main Street, Waltham, Massachusettes, 02154, U.S.A.
Tel. (617) 891-9380

California Measurements,

P.O. Box 594, Sierra Madre, California 91024, U.S.A.
Tel. (213) 355-3713

Canadian Applied Technology, Division of Arrow Flight
Holdings Limited,

2768 Slough Street, Molton, Ontario L4T 1G3, Canada
Tel. (416) 677-7861

Carleton Instruments Ltd.

2414 Holly Lane, Ottawa, Ontario K1V 7P1, Canada
Tel. (613) 731-4703

C.F. Casella & Co. Ltd.

Regent House, Britannia Walk, London Nl 7Nd, England
Tel.01 - 253-8581

Climet Instruments Co.

1320 West Colton Avenue, Redlands, California 92373, U.S.A.
Tel. (714) 793-788

Del Electronics Corp.

250 E. Sandford Blvd., Mount Vernon, New York 10550, U.S.A.
Tel. (914) 699-2000

D.M.E. Limited

P.O. Box 11026, Station H, Ottawa, Ontario, K2H 7T8, Canada
Tel (613) 829-1433

Dynac

Thompson's Point, Portland, Maine 04102, U.S.A.
Tel. (207) 774-5296

Environmental Systems Corp.

P.O. Box 2525, Knoxville, Tennessee 37901, U.S.A.
Tel. (615) 637-4741

Environment/One Corp.

2773 Balltown Rd. Schenectady, New York 12309, U.S.A.
Tel. (518) 346-6161

Fleming Instruments Ltd.

Caxton Way, Stevenage, Herts, SGI 2DE, England
Tel. Stevenage 3101-5
GII Enterprises Inc.,

P.O. Box 3356, Cherry Hill, New Jersey 08034, U.S.A.

Gardner Associates, Inc.

3643 Carman Road, Schenectady, New York 12303
Tel. (518) 355-2330

GCA/Technology Division

Burlington Road, Bedford, Massachusetts 01730, U.S.A.
Tel. (617) 275-9000

Gelman Instrument Co.

600 S. Wagner Road, Ann Arbor, Michigan 48106, U.S.A.
Tel (313) 665-0651

General Metal Works

8368 Bridgetown Road, Cleves, Ohio 45002, U.S.A.
Tel. (513) 941-2229

Hoskin Scientific Ltd.

1096 Victoria Ave., St. Lambert, Quebec J4R 1P7, Canada
Tel. (514) 672-1754

Imanco

40 Robert Pitt Drive, Monsey, New York 10952, U.S.A.
Tel (914) 356-3331

Laser Holography Inc.

1130 Channel Drive, Santa Barbara, California 93108, U.S.A.
Tel (805) 969-5077

Lear Siegler Inc. Environmental Technology Division

1 Inverness Drive East, Englewood, Colorado 80110, U.S.A.
Tel. (303) 770-3300

Leigh Systems Inc.

220 Boss Rd. Syracuse, New York 13211, U.S.A.
Tel (315) 437-2975

Levitt Safety Eastern Ltd.

33 Laird Drive, Toronto, Ontario, M4G 3S9, Canada
Tel (416) 425-8700

Meteorology Research Inc.

P.O. Box 637, Altadena, California 91001, U.S.A.
Tel (213) 791-1901

Mine Safety Appliance Co.

201 N. Braddock Ave., Pittsburgh, Pennsylvania 15208, U.S.A.
Tel (412) 241-5900

Misco Scientific

1825 Eastshore Highway, Berkeley, California 94710, U.S.A.
Tel. (415) 843-1282

National Environmental Instruments, Inc.

P.O. Box 590 Pilgrim Station, Warwick, Rhode Island 02888, U.S.A.
Tel (410) 738-3710

Philips Electronics Industries Ltd.

116 Vanderhoof Avenue, Toronto, Ontario M4G 2J1, Canada
Tel. (416) 752-1980

Phoenix Precision Instrument

Gardiner, New York 12525, U.S.A.
Tel. (914) 255-5000

Ralph E. Benner Ltd.

620 Supertest Road, Downsview, Ontario M3J 2M8, Canada
Tel. (416) 661-9400

Research Appliance Co.

Route 8, Gibsonia, Pennsylvania 15044, U.S.A.
Tel. (412) 443-5935

Royco Instruments Inc.

141 Jefferson Drive, Menlo Park, California 94025, U.S.A.
Tel (415) 325-7811

Sartorius-Membranfilter GmbH

34 Gottinger, Postfash 142, West Germany
Tel: (05 51) 308-1

Science Essentials Company

P.O. Box 6100, Anaheim, California 92806, U.S.A.
Tel (714) 634-3994

Sci-Med. Inc.

13010 County Road 6, Minneapolis, Minnesota 55441, U.S.A.
Tel. (612) 546-3504

Sierra Instruments Inc.

P.O. Box 909, Village Square, Carmel Valley, California 93924, U.S.A.
Tel. (408) 659-3177

Thermo-Systems Inc.

2500 Cleveland Avenue North, St. Paul, Minnesota 55113, U.S.A.
Tel (612) 633-0550

Weather Measure Corp.

P.O. Box 41257, Sacramento, Califormia 95841, U.S.A.
Tel. (916) 481-7565

Willer Engineering Ltd.

1800 Avenue Road, Toronto, Ontario, M5M 3Z1, Canada
Tel. (416) 783-3373

Willson Products Division, ESB Inc.

2nd and Washington Street, Reading, Pennsylvania 19603, U.S.A.
Tel. (215) 376-6161